THÈSE POUR OBTENIR LE GRADE DE DOCTEUR DE MONTPELLIER SUPAGRO

En Écologie Fonctionnelle et Sciences Agronomiques
École doctorale GAIA – Biodiversité, Agriculture, Alimentation, Environnement, Terre, Eau
Portée par l'Université de Montpellier

Unité de recherche UR 115 - AIDA-Agroécologie et Intensification Durable des Cultures Annuelles

LANDSCAPES AND LIVELIHOODS CHANGES IN THE NORTH-WESTERN UPLANDS OF CAMBODIA: OPPORTUNITIES FOR BUILDING RESILIENT FARMING SYSTEMS

Présentée par M. Rada KONG

Le 7 novembre 2019

Sous la direction de Jean Christophe CASTELLA

Devant le jury composé de

M. Jean-Pierre SARTHOU, Professeur, INP-ENSAT	Président du jury - Rapporteur
M. Ole MERTZ, Professeur, Université de Copenhagen	Rapporteur
Mme Agnès BEGUE, Chercheuse, CIRAD	Examinatrice
M. Philippe MERAL, Directeur de Recherche, IRD	Examinateur
Mme Malyne NEANG, Maître de Conférence, Royal University of Agriculture Cambodia	Examinatrice
M. Florent TIVET, Chercheur, CIRAD	Examinateur
M. Jean-Christophe CASTELLA, Directeur de Recherche, IRD	Directeur de thèse

UNIVERSITÉ DE MONTPELLIER

Montpellier SupAgro

Acknowledgements

This PhD dissertation is the result of my personal trajectory as a long time observer of the agricultural changes in the uplands of Cambodia and neighboring countries in Southeast Asia. A number of persons has guided me all along that discovery process.

During my master thesis research in Pailin Province, Cambodia in 2007, I witnessed the agricultural colonization of forestlands by successive waves of poor migrants who risked their life to clear land from the forest despite the landmines and the malaria. Like the **local farmers**, I was happy to see their fertile soils and high yields. At that time, they produced up to 10t/ha maize grain without fertilizers in newly reclaimed land. I seriously considered investing myself in farming because it was so easy to get rich with two harvests per year with low inputs.

Based on my agronomic knowledge, I knew for sure that these cropping systems would not last long. **Stéphane Boulakia**, who was my field advisor from CIRAD during MSc internship, showed me at Boskhnor research station how conservation agriculture (CA) could reverse the degradation process and make the cropping system sustainable. I was totally convinced thanks to empirical evidences from the CA experiments. At that time, I believed that the farmers would just adopt CA practices because they would see their interest in doing so, especially as the mechanization was saving labor and the cover crops were preserving the soil fertility.

Then, I received an Erasmus Mundus scholarship and did a second master research in Vietnam. In 2010, **Damien Hauswirth** from CIRAD supervised my field research in Son La Province. I discovered unbelievable landscapes, with steep slopes that I did not think could be cultivated. Hybrid maize was everywhere like in Pailin Province. The system was intensive as farmers put 400-500kg/ha NPK, but almost all practices were manual as mechanization was difficult with such rough terrain and steep slopes. The soil erosion and degradation was worse than in Pailin, my upland reference in Cambodia. I was thinking (and still today) that appropriate scale mechanization could help promoting CA there. First, I had to try with ‘my’ farmers in Pailin and Battambang Provinces.

In 2011, I resumed my work in the northwestern uplands of Cambodia with the PADAC project, led by Stéphane Boulakia. It was really challenging to codesign CA-based systems that would provide comparable economic benefits as conventional intensive practices (non-CA). We put many efforts in connecting different actors, i.e. farmers, input suppliers, traders, microfinance institution, around the promotion of CA practices. Our results were a little deceiving because we were in the middle of the maize boom, when all actors are happy with their productivity and don't see why they should change.

We introduced a subsidy package to buffer economic risks for the innovators, hoping that the profit would compensate the initial investment, and farmers would learn on the way. Unfortunately, the maize bust stage started around that time and most of CA plots generated lower economic benefit per hectare than non-CA. Farmers switched from maize to cassava but our CA-machinery was not adapted to this new crop. We were once again lagging behind farmers who were changing their practices faster than we could propose innovative practices based on our research results. We had only two planters imported from Brazil. Our efforts to copy the Brazilian no-till planter in Thailand did not succeed, as it was heavier and still too expensive for the local service providers. Under the guidance of **Florent Tivet** from CIRAD, we continued to provide no-till service to farmers with our two planters and kept discussing among team members how to bring CA practices to scale through innovative research methods.

Thanks to the support of **Florent Tivet** and **Jean-Christophe Castella** (IRD), I was awarded a research grant from the ACTAE project (Agence Française de développement - AFD) and the DESIRE and IPERCA projects (Agropolis Foundation). After a one-year struggle to find the required financial support, I could finally enroll in a PhD program at the GAÏA Graduate School in Montpellier. The enrolment would not have been possible without the support of my two host institutions, led by **Eric Scopel** the director of AIDA research unit of CIRAD, and **Malyne Neang**, the director of Ecoland Center of Royal University of Agriculture in Cambodia.

The distinghished members of my thesis committee, including **Agnès Bégué** (referent of the graduate school) and **Guillaume Lestrelin** (CIRAD-TETIS), **Jean Christophe Diepart** (Université de Liège), **Malyne Neang** (RUA), and **Florent Tivet** and **Stéphane Boulakia** (CIRAD-AIDA) provided a great support along the journey of my PhD. **Agnès Bégué** coordinated the exchanges between the graduate school and committee members. **Christine Casino** provided wonderful logistics at AIDA office. Financial support through CIRAD AI (Actions Incitatives) allowed me to comfortably stay in Montpellier to take the PhD courses and work under the supervision of the AIDA team. I also benefited from a 10-month mobility grant from ALFABET Erasmus Mundus that I was granted thanks to the support of **Didier Pillot** and **Cecile Durand** from Montpellier SupAgro.

My objectives with this PhD research were (i) to learn how to use participatory approaches to engage with stakeholders, (ii) to develop methods to keep agronomic studies relevant in the face of the rapid changes I had witnessed over the recent years; (iii) to produce empirical evidences that would convince donors and government agencies to support sustainable intensification of agriculture in Rotonak Monol district; and (iv) to build-up my own scientific competence and credibility about CA practices in Cambodia. Such research required to combine three approaches: i.e. land use and land cover change, farming systems, and simulation game. To be able to conduct the fieldwork, I had to learn remote sensing, GIS-based analysis and simulation game. **Elisa Belmain**, a MSc student in geography from Montpellier University, conducted her internship research in my PhD study site and trained me both in the field in Battambang and in the lab of TETIS in Montpellier, where I also got advised by **Agnès Bégué** and **Audrey Jolivot**.

I joined a one-week training on participatory land use planning supported by the EFICAS project in Luang Prabang and I also took part in the one-week training on Commod approach “La modélisation d’accompagnement: mettre des acteurs en situation pour partager des représentations et simuler des dynamiques” organized by Lisode in Avignon. In addition, I attended a short training on simulation game organized with the support of the ACTAE project and facilitated by **Patrick d’Aquino**. Thanks to these initial trainings, I could gain an initial understanding about the approach that I actually learnt on the job during the fieldwork supervised by **Jean-Christophe Castella**.

The Conservation Agriculture Services Center (CASC) of Department of Agricultural Land Resources Management (DALRM) of General Directorate of Agriculture (GDA) (**Suos Vuthy**, **Leng Vira**, **Sar Veng**, **Seng Raksmey**, and **Lay Vichet**) and GRET (**Pat Sovann**) provided support to field activities. I was assisted the three young enthusiastic interns (**Oum Somaly**, **Ek Sreykhouch**, and **Kaing Kong Seng**) from the Royal University of Agriculture for the household interview. The **local authorities** and **farmers** contributed a lot of their time to my participatory research.

My stay in Montpellier was enjoyable also because of the presence and support from Cambodian students (Kimchhin, Kimlong, Siv Mey, Sophea, Sothy, Veng, Sengly, etc.) and families (Bong Kim, Bong Soth, etc.) who were studying and living in Montpellier, respectively. With you, I had joyful gatherings and chitchat, which could release my stress and pressure from time to time. I would like to tell you how helpful it was and it created unforgotten memories of my stay in Montpellier.

The three articles that make up my PhD dissertation have highly benefitted from the endless help from **Jean-Christophe Castella**, **Florent Tivet**, **Jean Christophe Diepart** and **Guillaume Lestelin**. A long series of revisions taught me how to become a multi-faceted researcher with a large range of competences. These competences will definitely expand my professional opportunities in the field of sustainable development.

In conclusion, I would like to express my heartfelt appreciation to all of the persons mentioned here above, for their important contributions to my PhD research. I would also like to apologize with those who I forgot to mention. Last but not least, I would like to thank my lovely wife (**Sotheary**) who did not only bare all the burdens to take care of the kids (**Methea** and **Mony**), but also encouraged me to stand up and carry on, up to the end of this journey. I often tell my wife that this PhD study is for two students, you and me. I deeply thank you for making this journey possible!

Abstract

In Southeast Asia, the shift from a subsistence-based to a commodity-based agriculture is associated with the opening of the region to the market economy. The market globalization has been driving the adoption of "green revolution" technologies supported by the governments' policies to secure the food security and to accelerate the economic growth for the regional and global market integration. In the uplands, the shift involves the changes from upland rice and pulse crops with rotational systems to mono-cropping system of commodity crop such as maize and cassava. The farming has quickly colonized the forestlands in the frontiers, where complex land use dynamics are framed by insecure land tenure, weak law enforcement, inflow of migration, and market access. The rush to land is induced by the exponentially increasing demand of agricultural raw materials to feed the fast growing agro-industries along with the accelerating regional and international trading in particular with China. Consequently, the forest ecosystems and biodiversity are all lost as the clearance is done as big and fast as possible without regulations.

The newly cleared lands have been quickly degraded especially in the fragile upland agroecosystems due to the conventional practices that are generally based on the intensive tillage, chemical inputs, and mono-cropping system with short or no fallow period. These practices are promoted by the agro-industries that favor economies of scale by specializing their industrial processes with single commodities. A boom crop expands rapidly through massive adoption by smallholder farms through an imitative process, thanks to its high profitability. Specializing in the production of a single crop, so called crop boom, is highly risky in the sense that farmers are getting indebted to keep-up with increasing production costs and increasingly betting with the uncertainties of weather and market. Consequently, smallholders are forced to sell out the land and become wage laborer or migrant, while only a better off minority could cope with drawbacks of the boom crop, so called the bust stage, not because they anticipated it, but because they could accumulate enough capital. This creates a process of social differentiation with land concentration and wealth consolidation.

Even with such terrible consequences, the boom and bust cycles move to other forest frontiers because the newly cleared forestland is highly productive and the land tenure is not secured. The farmers opt for fast and high economic return crops such as maize and cassava and the agro-industries also flooded in there for those commodity crops. Moreover, there are no available sustainable agricultural land management and alternative soil conservation practices in those frontiers since all actors involved in the value chain enjoy their benefits and simply do not think of or ignore any conservation initiatives. Instead, the government

promote the foreign investment in agro-industries through the form of economic land concession with two fold objectives, first to improve the rural infrastructure and employment and second to accelerate the exportation of those commodities and diffuse the modern agricultural technologies introduced by the agro-industries to the farmers. Facing the vicious cycle of boom and bust and its consequences on the deterioration of landscape's functions and farmer's livelihoods, the pathways towards sustainable development are actively discussed to balance the socio-economic benefits with the integrity of the agroecosystem.

Redesigning a new model of agriculture after the destructive wave of the pioneer front and with most of the same actors as those involved in intensive monocropping is quite challenging. The socioeconomic environment may not be supportive to such a profound transformation. Agricultural researchers who promote agroecology face a number of challenges in a context of rapid changes, loose territorial governance, competing interests along value chains, and complex socioeconomic environments. They need to work at multiple scales, from multiple disciplinary perspectives, combining participatory diagnosis and co-design approaches, to remain relevant despite the rapidly changing land uses and context specific with broad scale implications for sustainable intensification.

Despite the influence of higher levels on their decisions, farmers are key agents of change, essentially because they have a direct stake into land-based practices; their live depend on it. This PhD research looks at farmers' decision-making as a lever toward (i) sustainable intensification from plot to landscape, (ii) bottom-up policy influencing strategy, and (ii) negotiation of alternative development pathways with market actors. Understanding the diversity of farming systems and their decisions making process is a prerequisite of any development intervention because the individual decisions influence agricultural development at higher levels. In addition, we may change intensification pathways by influencing farmers' decisions and other actors' along the value chain.

The northwestern uplands of Cambodia are one of the last forest frontiers in the region with rapid land use/cover changes (LUCC) associated with the consecutive boom-bust cycles of commodity crops, such as maize and cassava. The region is piloting conservation agriculture (CA) extension with the support the Ministry of Agriculture, Forestry and Fisheries (MAFF), and many lessons could be learnt on the agricultural innovation and the changes in farming systems. The objectives of the thesis are:

- To understand the complex interactions of factors that contribute to farmer's decision making in a context of rapid land use changes
- To support the sustainable intensification of upland agriculture through the definition of appropriate intervention mechanisms

The research addresses three specific objectives:

- To analyze the patterns and pace of land use and land cover changes (LUCC) in NW Cambodia over the recent decades and investigate their drivers at multiple scales,
- To characterize the current diversity of farming systems, how it was built-up in time; and their specific responses to changing socio-ecological environments,
- To investigate farmer's decision-making process and explore relevant intervention mechanisms through participatory simulations

I combined three different approaches to investigate farmers' decision-making. Land use change analysis based on chronological series of remote sensing data allows characterizing the speed and extent of changes. Converging evidences at multiple scales and from the perspective of multiple stakeholders were confirmed by quantitative and qualitative information from various sources: i.e. remote sensing data, socioeconomic data, and surveys of key resource persons. The diversity of land uses and land use changes reflects a diversity of farming systems who mobilize different practices and strategies to reach their goals and make decisions based on their specific resources and constraints both internal and external. I used a farming system approaches to understand the decisions made at farm and plot scales. I characterized farms diversity and trajectories at the district level and assessed their performances and capacity to innovate through a combination of structural and functional typologies based on quantitative and qualitative surveys. Lastly, I used simulation game with villagers to confirm and validate our understanding of farmers' decisions from plot to village scale. Then I used the game with representative farmers from different farm types to explore scenarios on the land use changes and innovation systems. I could thus identify intervention mechanisms to engage with farming communities into transformative pathways with appropriate intervention mechanisms towards sustainable intensification.

The LUCC analysis revealed dramatic changes with an increase of 65% agricultural land at the expense of the forest cover primarily between 2006-2016, when hybrid maize was introduced in the area. The political stabilization and rural migration drove agricultural expansion, while the crop diversification was driven by productivity decline and market uncertainties. Four main farm types were identified: Upland crop-based smallholder farm, Upland crop-based large farm, Land-poor off-farm income dominated farm, and Paddy based farm. The time of arrival, initial cash and labor, relationship with local authority, and/or social background are key factors defining farm's structure and determining their capacity to accumulate resources during the maize boom. This initial accumulation of resources / capital play important role to cope with the risks during the bust stage. The capacity to innovate is linked with the risks encountered and individual capacity to manage them, according to farm resource endowment, diversified land uses and opportunities for off-farm activities. The higher capacity to manage risks sustaining labor productivity through income diversification, the more willing they are to experiment new techniques and to innovate. Nevertheless, the decisions of all farm types are based on market opportunities and short term economic return with little attention to environmental aspect. They are still trapped in the boom-bust minset although the farmers in the CA villages are willing to adopt soil conservation practices and diversify their farms' activities.

The agricultural development model based on the rapid expansion of annual upland crops with "green revolution" technology is obviously not sustainable. However, the boom-bust cycle of commodity crops is likely to repeat as the actors in the commodity chains are well organized and integrated. The capacity to manage the risks and adapt to further changes will be limited, and for those in distress over-indebtedness, labor mobility outside agriculture is often the only coping mechanisms. The orchards plantation as an adaptation strategy of the better-off minority will face more risks with the pests and disease outbreaks due to biodiversity loss, and with the increasing shortage of water resources when all plantations reach productive stage for off-season production.

The use of role-playing game revealed the role of the CA project in changing farmers' perceptions and social learning that we could hardly investigate through individual interviews or group discussions. For example, we showed that the willingness of farmers to adopt CA-based cropping systems strongly relates to their perception of technical and economic risks and declining productivity. Even though the number of CA farms is still low, farmers evolved in their understanding of CA and changed their mindset and attitude in relation with boom crops when compared with the non-CA farmers/villages. The RADA game also revealed the need for more holistic approaches to innovation, notably to integrate a larger diversity of options addressing all components of farming systems. There is a need to generate and integrate new technical and organizational knowledge to negotiate solutions, to explore opportunities and to learn in different combined and integrated ways, facilitating the emergence of collective actions.

However, the weaknesses of social organizations and the prevalence of farmers' boom-crop mindsets were observed repeatedly during the games conducted in both CA and non-CA villages. It confirmed the lack of social cohesion within the farming community to collectively discuss and explore solutions. As recent migrants in a pioneer front region, farmers tend to work and decide individually as they share different living background and history. Other actors of the value-chains should drive the change toward agroecology practices by allocating price premium to agroecological products. Without any acknowledgement of the quality of agroecology products, farmers may follow the trends of new boom crops associated with a land concentration process.

Résumé étendu

1. Introduction

1.1 Les processus d’expansion et d’intensification agricole en Asie du Sud-Est

En Asie du Sud-Est, le passage d'une agriculture de subsistance à une agriculture commerciale est associé à l'ouverture de la région à l'économie de marché. La mondialisation des marchés a favorisé l’adoption de technologies dites de la « Révolution Verte » soutenues par les politiques publiques visant à garantir la sécurité alimentaire et à accélérer la croissance économique. Dans les terres hautes, les systèmes de subsistance à base de riz pluvial en rotation avec des légumineuses à grains ont été remplacés des cultures de rente telles que le maïs et le manioc. L'agriculture a rapidement colonisé les terres forestières, et les fronts pionniers caractérisés par un régime foncier peu sécurisé, une gouvernance faible, et un afflux incontrôlé de migrants. La ruée vers les terres est induite par une demande en augmentation exponentielle de matières premières agricoles pour nourrir les agro-industries en croissance rapide, ainsi que par l'accélération des échanges régionaux et internationaux, en particulier avec la Chine. En conséquence, les écosystèmes forestiers et la biodiversité disparaissent rapidement en l’absence de réglementations spécifiques.

Les terres récemment défrichées ont été rapidement dégradées, en particulier dans les agro-écosystèmes fragiles en raison des pratiques intensives généralement basées sur le travail mécanisé du sol, les intrants chimiques et les systèmes de monoculture avec une période de jachère courte ou nulle. Ces pratiques sont encouragées par les agro-industries qui favorisent les économies d’échelle en spécialisant leurs processus industriels. Les cultures de rente, très rentable initialement, se développent rapidement grâce à une adoption massive par les petites exploitations grâce à un processus d'imitation. Il est cependant très risqué pour les agriculteurs de se spécialiser dans la production d’une seule culture dans la mesure où ils s’endettent pour faire face aux coûts de production croissants et sont soumis aux aléas climatiques et aux fluctuations des marchés. En conséquence, les plus petits agriculteurs sont obligés de vendre leurs terres et de devenir travailleurs salariés ou d’émigrer, tandis qu’une minorité plus aisée peut faire face aux risques liées à l’agriculture intensive grâce au capital qu’il ont pu accumuler. Cela crée un processus de différenciation sociale avec concentration des terres et augmentation des inégalités économiques.

1.2 Explorer les voies d'une intensification durable de l'agriculture

L'intensification durable de l'agriculture nécessite de trouver un équilibre entre les bénéfices économiques et l'intégrité de l'agro-écosystème. L'intensification durable regroupe toutes les pratiques permettant de maximiser la production (de céréales, de tubercules ou de fibres) ou la productivité économique sans compromettre les potentialités productives des agro-écosystèmes cultivés pour la future génération d'agriculteurs. Co-concevoir un nouveau modèle d'agriculture après la vague destructrice du front pionnier et avec la plupart des mêmes acteurs que ceux impliqués dans la monoculture intensive est assez difficile. L'environnement socio-économique peut ne pas être favorable à une transformation aussi profonde. Un nombre croissant d'entreprises privées continuent de promouvoir des paquets technologiques comprenant des semences hybrides, des pesticides, des engrais minéraux, un travail du sol mécanisé, etc. Les politiques nationales de développement agricole ont également considérablement ouvert la voie aux monocultures intensives (ou cultures de boom). L'absence, ou la promotion très limitée, d'options de développement agricole en dehors du domaine des cultures de boom laisse les agriculteurs sans alternative convaincante. Pris dans une « logique du moindre effort », les agriculteurs mobilisent l'une ou l'autre de ces technologies facilement disponibles pour résoudre leurs problèmes à court terme sans être informés sur d'éventuels effets néfastes à long terme, jusqu'à leur apparition.

Dans le même temps, des institutions internationales telles que la FAO, le CIRAD et les agences de développement en faveur d'une intensification durable promeuvent un ensemble de pratiques alternatives telles que l'agriculture de conservation, l'agroforesterie, l'agriculture intégrée, la lutte intégrée, etc. Ces pratiques regroupées sous le terme « agroécologie » visent trois objectifs principaux : (i) augmenter les performances / productivité des systèmes de culture, (ii) préserver la fertilité des terres et la biodiversité et (iii) maintenir la résilience des systèmes de production agricole face aux aléas naturels et fluctuations économiques grâce à des sources de revenus diversifiées. Néanmoins, pour les agriculteurs qui cultivent des agro-écosystèmes de montagne fragiles, la promotion des pratiques de conservation rencontre un certain nombre de contraintes: (i) des contraintes biophysiques avec des terrains accidentés et des pentes abruptes qui limitent la conception d'options techniques économiquement viables; (ii) les conditions socio-économiques sont difficiles, la capacité d'investissement est faible avec un accès limité aux infrastructures, aux services publics et au marché pour la vente des produits et l'achat d'intrants; (iii) la promotion par les agroindustries de paquets technologiques standardisés est largement répandue et les agriculteurs recherchent généralement des solutions à court terme plutôt qu'à long terme; iv) jusqu'ici, les mécanismes de paiement pour services environnementaux ne constituent pas une option convaincante.

Les promoteurs de l'agroécologie font face à de nombreux défis dans un contexte de changements rapides, de gouvernance territoriale peu structurée, de conflits d'intérêts au sein des filières et d’environnements socioéconomiques complexes. Ils doivent travailler à plusieurs échelles, dans de multiples perspectives, en combinant des approches de diagnostic participatif et de co-conception, pour rester pertinents malgré les dynamiques d’usage de terres extrêmement rapides. Des recherches antérieures ont identifié des fenêtres d'opportunité d'intervention tout au long du cycle d'expansion-récession des cultures de boom. La promotion d’alternatives agroécologiques devrait intervenir avant le début du boom, lorsque les agriculteurs sont encore engagés dans une agriculture de subsistance ou après la phase de récession, une fois que les agriculteurs sont pleinement conscients des effets négatifs de la monoculture sur la fertilité des terres. De plus, les innovations proposées pendant la phase d'expansion du boom ne sont généralement pas suffisamment attractives du point de vue économique par rapport aux pratiques conventionnelles. Alors, devrions-nous, en tant que chercheur, laisser le boom des cultures se poursuivre jusqu'à ce qu'il conduise à sa propre perte, et ne rien faire ? Certainement pas. Nous devons nous engager dès que possible avec toutes les parties prenantes dans un processus collectif de conception des voies menant à une intensification durable. Les chercheurs deviennent alors des acteurs de la transition agroécologique par le biais d'un apprentissage collectif avec les communautés d'agriculteurs et tous les acteurs des filières et des territoires de production. Tous les acteurs doivent discuter et négocier pour proposer leurs propres voies vers une intensification durable, adaptées aux contextes locaux.

1.3 Les agriculteurs, agents clés du changement d’usage des terres

Les prix et la demande du marché sont des facteurs clés qui influencent la prise de décision des agriculteurs sur leurs choix de culture et pratiques culturales. Les agriculteurs optent généralement pour les cultures les plus rémunératrices qu'ils identifient et priorisent en prenant en compte les dimensions techniques, environnementales et économiques de la production. Les changements soudains dans les politiques commerciales et les spéculations financières ont une influence considérable sur les prix des produits agricoles. Étant donné que ces dimensions économiques mondiales dépassent le cadre et le mandat des opérateurs de développement, ils privilégient sur le terrain le renforcement des capacités adaptatives et de la résilience des populations locales face aux événements imprévisibles et aux bouleversements économiques.

En dépit de l'influence des niveaux supérieurs sur leurs décisions, les agriculteurs sont des agents clés du changement, du fait de leurs pratiques de gestion des terres agricoles dont leur vie dépend.

Cette thèse de doctorat examine la prise de décision des agriculteurs comme un levier vers (i) une intensification durable de la parcelle jusqu’au paysage, (ii) une stratégie d’influence des politiques et (ii) la négociation de voies de développement alternatives. La compréhension de la diversité des systèmes agricoles et de leurs processus décisionnels est une condition préalable à toute intervention de développement, car les décisions individuelles prises en matière de choix de culture et de pratiques culturales ont un impact sur le développement agricole à des niveaux plus élevés. En outre, nous pouvons modifier les voies d'intensification en influençant les décisions des agriculteurs et des autres acteurs des filières.

Dans de nombreux modèles de décision, les agriculteurs sont représentés sous forme d'agents rationnels qui maximisent les avantages économiques tirés de ressources limitées, ce qui conduit à une programmation linéaire et à des techniques d'optimisation. Les stratégies des agriculteurs tendent à optimiser les activités de la ferme en fonction du capital, des connaissances disponibles et des risques anticipés dus à des facteurs externes, par exemple : aléas climatiques et fluctuations des marchés. Les relations entre la structure et le fonctionnement des exploitations sont également étudiées, car les ménages agricoles présentant des caractéristiques similaires en termes de moyens de subsistance, d'activités et de contraintes, sont supposés développer des stratégies similaires. Les typologies d'exploitations agricoles utilisent couramment des enquêtes sur des échantillons de ménages et couvrent un large éventail de paramètres. Cette approche est utilisée pour caractériser les processus décisionnels de différents groupes d'agriculteurs regroupés dans une typologie d'exploitations. Les modèles sont fondés sur une analyse multivariée afin de déterminer les paramètres contribuant aux décisions en matière d'usage des terres ou d'innovation. Reconnaissant qu'un grand nombre de contraintes (psychologiques, socio-économiques, institutionnelles, environnementales et politiques) influencent le décideur, des modèles de décision fondés sur cette rationalité ont également été développés pour explorer la diversité des systèmes de production agricoles.

En outre, des approches participatives, telles que celles fondées sur l'articulation de jeux de rôles et de modèles multi-agents, sont utilisées pour impliquer toutes les parties prenantes dans la résolution des problèmes de gestion des terres et de soutien à l'innovation. Les chercheurs co-conçoivent le modèle de décision avec d'autres acteurs et le font évoluer en fonction de scénarios sur la gestion de ressources naturelles communes. Cette approche est également utilisée pour soutenir l'apprentissage collectif sur la gestion des biens communs et l'exploration de compromis entre des objectifs contradictoires associés à différents modèles de décision. Pour avoir un impact au niveau du paysage, tous les acteurs, des agriculteurs aux décideurs politiques, doivent être impliqués.

2. Site d'étude dans les hautes terres au nord-ouest du Cambodge

Les hautes terres du Cambodge dans la région nord-ouest illustrent la dynamique d'usage des terres largement observée dans la région. Notre zone d'étude était recouverte de forêt dense jusqu'à la fin des années 1990. Elle abritait les derniers fiefs des Khmers Rouges qui combattaient le gouvernement cambodgien, jusqu'à l'accord de paix de 1998. Après cette période, les Khmers rouges ont réintégré le gouvernement et la guerre civile cambodgienne a officiellement pris fin. Suite à l'attribution de terres forestières à des soldats démobilisés dans le cadre des accords de paix, ces zones sont devenues l'un des derniers fronts pionniers de la région.

La conversion des terres forestières en terres agricoles a été massive et rapide, sous l'effet de deux facteurs successifs. Premièrement, les vastes forêts disponibles ont attiré un important flux migratoire depuis les zones de plaine voisines, où les terres étaient saturées. La pénurie de terres dans les plaines alluviales a poussé les agriculteurs pauvres à s'approprier les terres situées dans les hautes terres périphériques. Deuxièmement, alors que l'arrivée des migrants se poursuivait, l'augmentation du prix des terres grâce aux revenus élevé de l'agriculture a poussé la première vague de migrants à agrandir ou à vendre leurs terres récemment défrichées et à s'approprier ou acheter des terres forestières à un prix inférieur plus loin, dans les marges forestières. L'amélioration de l'accès au marché et l'introduction de semences de maïs hybride ont été les principaux moteurs du boom du maïs qui s'est produit au Cambodge de 2006 à 2012.

En 2009, préoccupé par les conséquences environnementales désastreuses de la monoculture intensive de maïs, le ministère de l'Agriculture, des Forêts et de la Pêche a lancé un programme de recherche et développement sur l'agriculture de conservation avec le soutien technique du Cirad. Son objectif était de concevoir des pratiques culturales alternatives aux systèmes de monoculture intensifs qui s'étaient rapidement répandues depuis 2006. Le programme a développé des activités pilotes dans les zones d'étude, fondées sur deux approaches ; d'abord un paquet technique subventionné en agriculture de conservation de 2010 à 2012, et ensuite, avec la fourniture de prestations de service et de conseils techniques à partir de 2013. Les options techniques proposées résultaient d'un processus de co-conception (Husson et al., 2016). Bien qu'elles répondent aux trois objectifs de l'intensification durable, les agriculteurs n'ont que faiblement adopté les pratiques proposées, même subventionnées, car leurs avantages économiques étaient inférieurs à ceux des pratiques conventionnelles basées sur le travail du sol et les herbicides. De plus, le prix payé aux agriculteurs était le même pour le maïs produit avec des techniques d'agriculture de conservation (AC) et non-AC.

L'intérêt des agriculteurs pour le maïs AC a augmenté pendant la phase de récession du cycle de boom, mais la majorité des agriculteurs ont réagi à la baisse des rendements du maïs en passant à une autre culture de boom, le manioc, au lieu d'adopter des pratiques d'AC basées sur le maïs. Le processus de co-conception de systèmes de culture en AC était en quelque sorte en retard sur les transformations rapides d'usage des terres ou pâtissait d'un manque d'appui de la part d'opérateurs de développement pour faciliter l'accès à des moyens de production spécifique en AC (machinisme, semences) et d'accompagnement technique des agriculteurs. Au moment de la rédaction de ce document, où les pratiques d'AC pour le manioc sont disponibles après une nouvelle période de co-conception suivie d'une période pilote de validation, les agriculteurs sont déjà passés à une autre culture de boom, la mangue. Les chercheurs sont confrontés à l'extrême rapidité des changements d'usage des terres et doivent constamment adapter leurs approches, options techniques proposées et méthodes d'intervention, au contexte spécifique des hautes terres de l'ouest du Cambodge. D'autre part, les histoires de boom de cultures se répètent dans le temps et l'espace dans toute l'Asie du Sud-Est et les leçons tirées de notre site d'étude situé dans le nord-ouest du Cambodge seront utiles pour les agriculteurs subissant des changements similaires dans d'autres régions. Finalement, notre recherche vise à mettre fin à la malédiction des cycles de boom en concevant avec les parties prenantes des méthodes de recherche pertinentes et des mécanismes d'intervention permettant une intensification durable, tant au niveau de l'exploitation agricole que du paysage.

3. Objectifs et méthodes

Les objectifs de la thèse sont :

- comprendre les interactions complexes entre facteurs qui contribuent à la prise de décision des agriculteurs dans un contexte de changements rapides d'usage des terres,
- soutenir l'intensification durable de cette agriculture pionnière par la définition de mécanismes d'intervention appropriés.

Pour se faire, nous nous sommes donnés trois objectifs spécifiques :

- analyser les dynamiques d'utilisation des terres dans le nord-ouest du Cambodge au cours des dernières décennies et étudier leurs moteurs à de multiples échelles,
- caractériser la diversité actuelle des systèmes de production agricole, comment elle s'est construite dans le temps; et leurs réponses spécifiques à l'évolution des environnements socio-écologiques,
- étudier le processus décisionnel de l'agriculteur et explorer les mécanismes d'intervention pertinents au moyen de simulations participatives

Pour atteindre ces objectifs, nous avons combiné trois approches différentes du processus décisionnel des agriculteurs (Figure 1). L'analyse des changements d'usage des terres, fondée sur une série chronologique de données de télédétection, permet de caractériser la vitesse et l'ampleur des changements. Des données convergentes à différentes échelles et du point de vue de multiples parties prenantes ont été confirmées par des informations quantitatives et qualitatives provenant de diverses sources : données de télédétection, données socioéconomiques et enquêtes auprès de personnes-ressources clés.

La diversité d'usage des terres et les changements d'affectation des sols reflètent la diversité des systèmes de production agricole qui mobilisent différentes pratiques et stratégies pour atteindre leurs objectifs et prennent des décisions en fonction de leurs ressources et contraintes spécifiques, internes et externes. Nous utilisons une approche de type système de production agricole pour comprendre les décisions prises à l'échelle de la ferme et de la parcelle. Nous caractérisons la diversité et les trajectoires des exploitations agricoles au niveau régional et évaluons leurs performances et leurs capacités à innover grâce à une combinaison de typologies structurelles et fonctionnelles basées sur des enquêtes quantitatives et qualitatives.

Enfin, nous avons développé un jeu de simulation avec les villageois pour confirmer et valider notre compréhension des décisions des agriculteurs de la parcelle jusqu'au village. Nous avons ensuite utilisé le jeu avec des agriculteurs représentatifs de différents types d'exploitations agricoles pour explorer des scénarios de changement d'usage des terres et des systèmes d'innovation agricole. Nous avons ainsi identifié des mécanismes d'intervention pour engager les communautés agricoles dans des voies d'intensification durable.

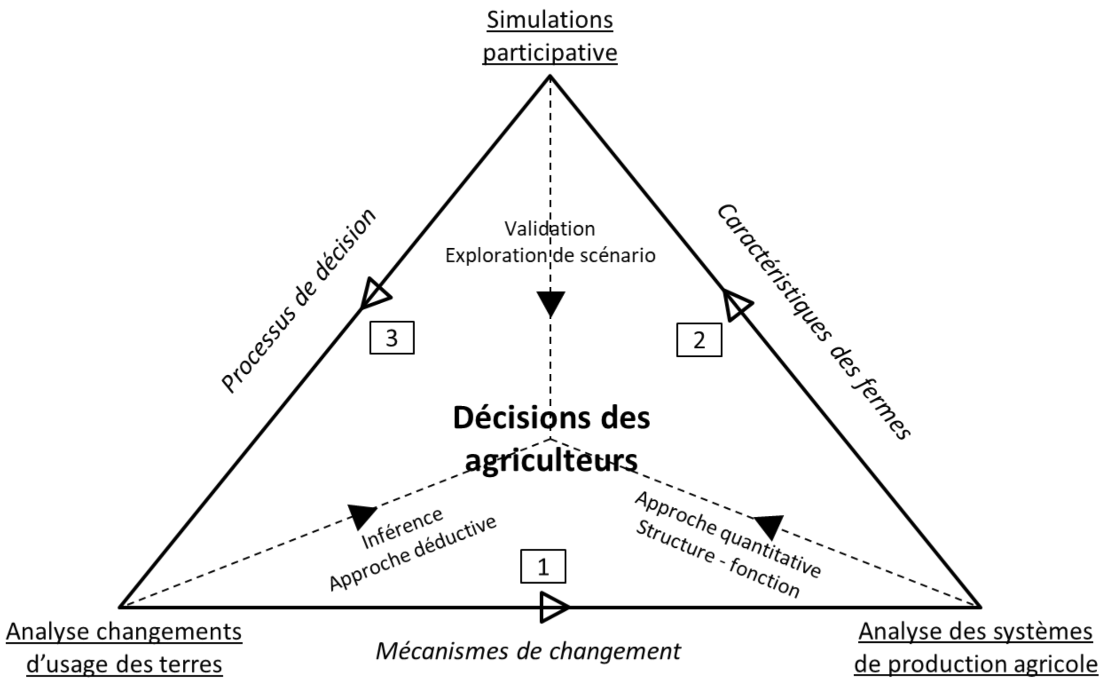


Figure 1 : Cadre méthodologique

4. Résultats

La thèse examine la complexité des dynamiques d'utilisation des sols associés aux cycles d'expansion et de récession des cultures de boom, telles que le maïs et le manioc. Ces dynamiques s'inscrivent dans un modèle de développement agricole qui repose sur l’expansion rapide des cultures annuelles de terres hautes et sont soutenues par une technologie type « révolution verte ».

4.1 Vulnérabilité accrue des systèmes de production agricole

Les changements agraires survenus au cours des deux dernières décennies à Rotonak Mondol ont suivi un schéma similaire à celui décrit dans d'autres régions de la région du Mékong (Vietnam, Laos, Thaïlande, Myanmar). Une culture pionnière (le maïs) soutenue par des marchés favorables et une industrie agro-alimentaire en plein essor a tout d'abord suscité l'enthousiasme des petits exploitants agricoles et a attiré des migrants de tout le pays. La logique dominante était avant tout économique et visait à générer rapidement des revenus monétaires de l’activité agricole. La monoculture du maïs basée sur un labour répété s'est ainsi développée massivement après la déforestation. Des marchés puissants assurant l'accès aux intrants et la vente des produits a permis à des acteurs de structurer rapidement des filières agricoles, dans lesquelles les institutions de micro-finance ont un rôle non-négligeable. Les premiers résultats ont été très encourageants, à la fois en termes de rendement et de rentabilité économique. Mais l’enthousiasme des premières heures a été de courte durée pour les agriculteurs. Les niveaux de rendement ont rapidement chuté et les épidémies de toutes sortes ont augmenté en raison des pratiques monoculturales. La productivité des terres et de la main-d'œuvre - mesurée en valeur ajoutée par hectare et par main-d'œuvre active - a donc diminué. La perte de productivité a été compensée par l'utilisation accrue d'engrais et de pesticides, ce qui a encouragé l'endettement auprès d’institutions de micro-finance.

Quelques années plus tard, le manioc est apparu comme une nouvelle culture de boom, portée par des marchés forts et des réseaux d'acteurs commerciaux (souvent les mêmes) bien articulés aux agro-industries régionales. Les opportunités offertes par le manioc ont suscité le même enthousiasme chez les agriculteurs, animés de la même logique : générer un profit à court terme en adoptant des techniques simples pour cultiver des cultures très demandées sur le marché. Dans une certaine mesure, le manioc a remplacé le maïs mais a également entraîné une deuxième vague de déforestation. Et l'histoire se répéta. Après les premières années d'expansion, le rendement et la rentabilité du manioc ont diminué. Les effets de la récession étaient d'autant plus marqués que les ressources forestières avaient progressivement disparus, limitant l'expansion des terres agricoles. Le processus d’intensification de l’agriculture a également eu un impact sur le potentiel productif des terres agricoles, les labours répétés ayant entraîné un épuisement de la fertilité des sols et, de manière générale, leur dégradation.

Ces processus ont rendu les systèmes agricoles plus vulnérables en limitant leur capacité d'adaptation à de nouveaux changements. Par ailleurs, les agriculteurs sont de plus en plus exposés aux risques associés à la volatilité des prix des produits agricoles et aux aléas météorologiques, ce qui met en péril leurs moyens de subsistance. Ceux qui disposent de ressources suffisantes parviennent à joindre les deux bouts. Mais pour ceux qui sont en situation de surendettement ou dont les terres agricoles sont trop dégradées, la mobilité de la main-d'œuvre en dehors de l'agriculture est souvent le seul mécanisme d'adaptation.

Les agriculteurs qui en ont les moyens se sont tournés vers les cultures pérennes d’arbres et de vergers comme les manguiers et les longanes, animés de nouveau par la même logique de cultures de boom. Les vergers accommodent des sols dégradés et l'installation des systèmes d'irrigation requis pour la production hors saison peut en partie résoudre le problème de la variation des précipitations. Cependant, la production hors saison ne peut pas toujours bénéficier de conditions de marché favorables car les prix sont également très variables, comme au début de 2019 avec une baisse du prix des longanes. L'utilisation d'insecticides et de fongicides a également augmenté dans la mesure où la diminution de la biodiversité n’a pas été compensée par une lutte antiparasitaire intégrée. L'augmentation considérable du nombre de vergers, et en particulier de la production hors saison de longanes et de manguiers, soulève des inquiétudes quant à la disponibilité des ressources en eau. Au cours de nos enquêtes, la plupart des chefs de commune du district de Rotonak Monol ont fait part de leurs préoccupations concernant l’utilisation croissante de pesticides et des tensions entre l’agriculture et les ménages pour l'utilisation de l'eau. Par conséquent, les systèmes agricoles spécialisés dans la production de vergers hors saison sont également vulnérables.

4.2 Homogénéisation des paysages et différenciation des systèmes de production

Dans le mesure où les agriculteurs partagent le même enthousiasme pour les cultures de boom et ont tendance à s’imiter, la vulnérabilité socioécologique au niveau des systèmes agricoles se reproduit au niveau du paysage. En moins de dix ans, les forêts de Rotonak Monol se sont converties en paysages agricoles homogènes grâce à la monoculture de maïs et de manioc. Avec l’extension des plantations d’arbres fruitiers, on observe un processus de diversification caractérisée par la formation de mosaïques de maïs hybride, de champs de manioc, de vergers de manguiers / longanes associés ou non à d’autres espèces telles que la papaye et la banane. La tendance récente aux cultures arboricoles pourrait potentiellement maintenir ou restaurer la qualité du sol qui a été dégradé par des techniques de culture non durables basées sur un travail du sol intensif. Cependant, la gestion des cultures intercalaires avec labour et l'utilisation croissante de pesticides peuvent entraîner des problèmes environnementaux supplémentaires. Si leur prix tombe trop bas, les plantations de manguiers pourraient être reconverties en cultures annuelles ou en une autre plantation d’arbres fruitiers. Le retour de la monoculture renforcerait alors les risques d'épidémies d'organismes nuisibles et de pollution de l'eau. En bref, les paysages agricoles simplifiés et homogènes sont plus sensibles à la variabilité du marché et leur capacité d'adaptation écologique est également affectée.

Puisque les agriculteurs ne sont pas économiquement égaux pour faire face à ces transformations et s'y adapter, les impacts de ces transformations agricoles sont socialement différenciés. Les ménages les plus vulnérables, dotés de petites fermes, ont tendance à perdre proportionnellement plus que d'autres lors de la phase de récession. Le surendettement entraîne très souvent une décapitalisation par la vente de terres et/ou une migration de la main d'œuvre. Les revenus de ce groupe de ménages se restructurent progressivement vers le salariat. Un autre groupe d'agriculteurs réussi à s'en sortir, mais reste vulnérable, en particulier vis-à-vis de l'endettement. Ils dépendent également de la main-d'œuvre salariée et parfois de la migration de la main d'œuvre pendant les mauvaises années, mais ont tendance à investir davantage dans l'agriculture pendant les bonnes années. Une troisième catégorie de producteurs dispose de suffisamment de ressources pour absorber les chocs et élargir leur base foncière agricole. Ils sont plus impliqués dans les innovations agricoles et leur revenu dépend moins du travail salarié et des emplois liés à la migration. Ils ont tendance par ailleurs à embaucher du travail salarié. Même s'ils profitent des opportunités offertes par les cultures de boom, ils sont aussi vulnérables aux risques associés à la phase de récession.

Toutefois, ces trois types de ménage n'évoluent pas de manière indépendante et les changements agricoles transforment les rapports sociaux de production entre eux. Les ménages riches en main-d'œuvre et pauvres en terres ont tendance à vendre leur travail à des ménages riches en terres avant de se consacrer à des activités salariales en dehors du village. De nouvelles relations sont également associées à l'activation du marché foncier au sein des communautés et à un processus de concentration des terres qui se développe au sein même des communautés. Ce processus assez classique de polarisation (de la terre d'une part et de la main-d'œuvre de l'autre) est exacerbé par les acteurs extérieurs (riches agriculteurs migrants, citadins) qui achètent des terres dans les villages pour devenir des producteurs agricoles.

Dans un tel contexte, un scénario de statu quo ne semble pas prometteur. Les agriculteurs ont connu les conséquences négatives liées aux cycles d'expansion et de récession et sont bien conscients des problèmes qui y sont associés. Cependant, ils ne sont pas en mesure de briser le cycle, car ils restent enfermés dans une logique de retour économique rapide qui prime sur toute considération environnementale ou sociale à long terme. Plus fondamentalement, cet état d'esprit est influencé par deux facteurs principaux. D'une part, les intermédiaires commerciaux de ces nouvelles filières sont bien organisés pour assurer le développement des cultures de boom. Au Cambodge, les politiques de développement agricole sont également très favorables aux cultures de boom et il existe peu de soutien politique pour promouvoir les alternatives. Par ailleurs, les communautés rurales sont principalement constituées de migrants qui ne partagent pas nécessairement la même histoire ni une vision commune du développement de leur territoire. Ce manque de cohésion sociale limite la capacité de la communauté à capitaliser ses expériences au sujet des cultures de boom et à prendre des mesures pour briser les cycles de boom et de récession. Au lieu de cela, la tendance est plutôt à des comportements individualistes en période de difficultés.

Le statu quo est caractérisé par une tension entre la recherche de la nouvelle culture de boom, reproduisant une logique sans issue, et la volonté des agriculteurs de rompre le cycle. Il est peu probable qu'un autre essor des cultures annuelles de terres hautes survienne après le manioc car le sol est déjà très appauvri, les coûts de production augmentent, les fonctions de lutte contre les ravageurs de l'écosystème se sont détériorées et le marché mondialisé ne peut plus garantir un prix élevé à long terme comme c'était le cas avant avec le maïs.

5. Discussion

A partir de 2010, le projet PADAC a proposé des alternatives au cycle d'expansion-récession du maïs et manioc en testant une diversité de systèmes de culture en agriculture de conservation. Les enseignements tirés du projet doivent permettre de concevoir des mécanismes d'intervention appropriés aux changements rapides des systèmes de production et à identifier de nouvelles voies pour une transition agro-écologique.

5.1 Leçons du projet PADAC (2009-2013) et de la période post-PADAC (2014-2018)

L'approche DATE (Husson et al., 2016) a été suivie en réalisant dans un premier temps un diagnostic agraire et en conduisant des expérimentations basées sur des références techniques développées dans la province de Kampong Cham (région Centre-Est) de 2004 à 2009. Une gamme de systèmes de culture sur couvert végétal (SCV) a été évaluée pour les principales cultures annuelles en intégrant une diversité de plantes de couverture et une mécanisation spécifique pour ces systèmes. Les systèmes de culture les plus prometteurs à base de maïs ont été comparés aux systèmes conventionnels à partir de tests effectués par des agriculteurs volontaires impliqués dans un réseau de vulgarisation pilote. Ces systèmes de culture innovants ont été testés simultanément au sein de parcelles expérimentales et au sein de ce réseau. En raison d'un certain nombre de contraintes et défis, les résultats n'ont pas répondu aux attentes initiales d'inversion du processus de diminution de fertilité des sols tout en maintenant des niveaux de rentabilité supérieurs aux systèmes conventionnels. J'ai traduit ces contraintes et défis en leçons afin d'explorer de nouveaux mécanismes d'intervention pour une transition agroécologique.

L'un des principaux défis rencontrés a été l'évolution rapide de la demande du marché régional pour de la production de maïs substituant des cultures de légumineuses pratiquées initialement chez les agriculteurs pionniers. A la fin du boom du maïs, le manioc est devenue la culture dominante pendant quelques années suivies de vergers de manguiers et longaniers. La demande du marché a toujours été un moteur essentiel du développement de ces fronts pionniers. Par exemple, l'augmentation importante de la superficie cultivée de manioc au Cambodge à partir des années 2010 est à rattacher à la baisse de production en Thaïlande due à la prévalence de cochenille dans les principales régions de production. L'évolution des opportunités de marché est devenue une contrainte majeure lorsque les changements des systèmes de culture et de production sont devenus plus rapides que le temps minimum requis pour évaluer les performances et les impacts environnementaux. Même avec des sites de démonstration, où le projet concevait des systèmes de culture diversifiés avec un grand nombre de cultures, il était difficile d'avoir une réactivité suffisante pour suivre ces changements rapides ; la fenêtre d'opportunité pour adapter et promouvoir les systèmes de culture alternatifs étant extrêmement étroite. De plus, l'absence d'opérations de développement conçues et mises en œuvre conjointement avec des acteurs locaux a définitivement été un obstacle majeur à la promotion et l'adaptation de ces innovations.

Malgré les subventions accordées par le projet pour atténuer les risques encourus par les agriculteurs qui investissaient dans la diversification des cultures (cultures principales et cultures de couverture), ceux-ci hésitaient à appliquer de nouveaux ensembles techniques tant que la rentabilité de leurs systèmes de production était toujours acceptable. Les agriculteurs ont perçu ces pratiques (arrêt du labour, utilisation de plantes de couverture et d'engrais minéraux) en rupture par rapport à la gestion conventionnelle de leurs systèmes. Dans une telle dynamique de « boom crop » l'adoption d'innovations ou de nouvelles pratiques doit en premier lieu répondre aux attentes à court terme des agriculteurs avec une diminution significative des intrants, de la main-d'œuvre et/ou des coûts de production, avec pour résultat direct une augmentation de la rentabilité de la terre et/ou de la main-d'œuvre. Le projet s'est adapté à ces attentes en modifiant son approche en matière de soutien à l'innovation pour passer d'un programme technique complet à une offre de service sur la base de prestations privées associée à un service de conseil à partir de 2013. L'équipe du projet a joué un rôle de prestataire de services proposant des services de semis direct ainsi qu'une assistance technique qui était prise en charge sur fonds public. Il s'agissait de maintenir une dynamique de réseau d'agriculteurs autour de différents éléments techniques propres à l'agriculture de conservation. Cette approche a permis de préserver un terrain d'apprentissage pour les agriculteurs, les prestataires de services en interaction avec les équipes du projet.

Cette analyse plaide en faveur du maintien de parcelles expérimentales dans les exploitations afin de jouer le rôle de « balises technologiques », dans le cadre desquelles des systèmes de culture co-conçus sont comparés les uns aux autres pendant plusieurs années, parallèlement aux pratiques agricoles passées et actuelles. Une telle approche démontrerait les performances des systèmes de culture innovants (i) après la conversion avec une amélioration progressive de la fertilité des sols et (ii) en tenant compte de la variabilité interannuelle des conditions climatiques.

5.2 Leçons et perspectives du jeu RADA

L'utilisation de jeux de rôle a révélé le rôle positif du projet dans le changement des perceptions des agriculteurs et de l'apprentissage social sur lequel il nous était difficile d'enquêter sur la base d'entretiens individuels ou de discussions de groupe. Ces jeux ont mis en évidence que l'adoption de systèmes de culture basés sur l'AC est étroitement liée à la perception des risques techniques, économiques et d'une baisse potentielle de productivité les premières années. De toute évidence, la qualité des processus participatifs était liée à la compréhension des bénéfices et contraintes des pratiques d'agriculture de conservation.

Le jeu RADA a également révélé la nécessité d'approches plus globales en matière d'innovation, notamment pour intégrer une plus large diversité d'options couvrant toutes les composantes des systèmes agricoles. Il est également indispensable de générer et d'intégrer de nouvelles connaissances à la fois techniques et organisationnelles pour explorer de nouvelles opportunités et faciliter l'émergence d'actions collectives.

Le jeu RADA n'explorait pas explicitement les scénarios incluant les options techniques et organisationnelles pour une transition agroécologie. En raison du processus de diversification en cours, avec des associations de cultures annuelles et pérennes, un certain nombre d'options agroécologiques, telles que des systèmes agroforestiers, une plus large intégration agriculture - élevage, pourraient être testées pour améliorer l'efficience des systèmes de production et préserver la production de services écosystémiques dans ces territoires. Il n'existe pas de solution unique et de nombreuses études sur l'innovation agricole encouragent la co-production de connaissances pour stimuler les niches d'innovation et favoriser la transition vers une intensification durable. Le jeu RADA pourrait aider à explorer de tels scénarios en mobilisant les leçons apprises collectivement au cours de la période PADAC, au cours des dernières années et en facilitant une plus large implication du secteur privé local.

Les résultats du jeu ont confirmé l'impact positif du projet PADAC sur (i) le développement des compétences non techniques en relation avec les connaissances techniques (par exemple, la conservation des sols, la gestion des risques) et (ii) la capacité organisationnelle avec le contrôle du feu, par exemple. Bien que le nombre d'agriculteurs et d'hectares en AC soit faible, les agriculteurs ont évolué dans leur compréhension de l'AC, ils ont une connaissance plus large de l'impact des grandes cultures comparativement aux agriculteurs et aux villages non AC. Le travail de l'équipe PADAC a permis l'émergence d'un réseau hybride d'agronomes, chercheurs, d'agents de vulgarisation, de prestataires de services et d'agriculteurs grâce à leurs expériences communes sur un grand nombre de cultures, de pratiques et d'outils qu'ils mobilisent encore plusieurs années plus tard. Les compétences techniques acquises au fil des années représentent un atout précieux pour le secteur de l'agriculture du Cambodge.

Cependant, les faiblesses des organisations sociales ainsi que la prédominance d’un mode de fonctionnement individuel ont été observées à maintes reprises au cours des jeux organisés dans les villages CA et non-CA. Cela a confirmé le manque de cohésion sociale au sein des communautés rurales pour discuter collectivement et explorer de nouvelles alternatives et scénarios. En tant que migrants récents dans une région pionnière, les agriculteurs ont tendance à travailler et à décider individuellement ne partageant pas les mêmes antécédents et ayant connu des trajectoires distinctes.

Le secteur agro-industriel doit également être moteur de cette transition en valorisant des produits agroécologiques qui sont de plus en plus demandés par les consommateurs. En l’absence de rétribution pour la qualité des produits agroécologiques et/ou sans soutien à la production de services écosystémiques (carbone du sol, qualité de l’eau …), les agriculteurs resteront prisonniers de ces modes de production avec des cycles successifs de ‘boom crops’ qui sont associées à un processus de concentration progressif des terres. L'augmentation rapide de la surface dédiée aux fruitiers soulève de nouvelles questions qui sont liées (i) à la stabilité de la demande (national, régional), (ii) à l’offre en main-d'œuvre et (iii) à la disponibilité des ressources en eau indispensable pour des productions de saison sèche. Il est nécessaire d’analyser à moyen terme l’évolution de ces trois facteurs et comment aborder ces différentes tensions entre accès à l’eau pour les communautés et eau agricole et quels besoins de main-d’œuvre pour les opérations de production, de post-récolte en lien avec le flux actuel de main-d’œuvre en provenance d’autres provinces.

Le jeu RADA pourrait être étendu à l’échelle des villages et des communes en utilisant des approches de théâtre participatif pour sensibiliser à la dégradation des terres, aux conséquences négatives des cycles d'expansion et de ralentissement des monocultures, explorer des systèmes alternatifs et les conditions nécessaires à leur émergence.

6. Conclusions

Ma thèse de doctorat a combiné trois approches, à savoir (i) l’analyse de l’usage des terres, (ii) la caractérisation des trajectoires des systèmes de production agricoles, et (iii) des simulations participatives avec un jeu de rôle, dans un cadre méthodologique unique (Figure 1) pour comprendre la complexité et la rapidité des dynamiques agraires d’une zone de front pionnier. L'analyse du changement d'usage des terres à partir d’images de télédétection a permis de caractériser et de quantifier les changements, puis de définir ses moteurs et ses acteurs afin que des mécanismes d'intervention pertinents puissent être proposés. L'analyse des systèmes de production agricole a été mobilisée pour évaluer la diversité des exploitations agricoles en fonction de leurs contraintes et de leur capacité d'innovation. Le jeu de simulation participative a recréé le contexte décisionnel des agriculteurs qui a prévalu pendant le boom du maïs pour explorer des scénarios de gestion des terres et engager les participants dans un apprentissage collectif. Chaque approche a ses avantages et ses contraintes. En les combinant, nous avons développé une démarche holistique capable de capturer les changements très rapides qui ont complètement transformé les paysages et les modes de vie en quelques années. La rapidité des changements auxquels nous faisions face était un grand défi méthodologique. J'ai conçu ce cadre méthodologique afin de 'saisir' la vague de transformation, ses moteurs et ses impacts, de manière significative pour les acteurs locaux afin qu'ils puissent en tirer des leçons et agir en conséquence pour contribuer à l'intensification durable de l'agriculture. Intégrer ces trois approches dans ma thèse de doctorat était un vrai défi, car je devais me former aux trois approches pour pouvoir les mettre en synergie. Ma recherché a confirmé l'intérêt de ce cadre méthodologique novateur en le mettant à l'épreuve du terrain pour étudier les cycles d'expansion et de récession des cultures de boom dans les contextes en mutation rapide de fronts pionniers. La combinaison systématique de méthodes qualitatives et quantitatives à plusieurs échelles d'espace (de la parcelle à la ferme et au niveau du paysage) et de temps a ajouté de la valeur à l'approche scientifique proposée.

L'analyse des données de télédétection a dévoilé une dynamique de front pionnier spectaculaire, avec des terres forestières largement converties en terres agricoles et une transition rapide des légumineuses vers le maïs, puis du maïs vers le manioc et enfin du manioc vers des fruitiers. L'analyse était basée sur des informations convergentes recueillies à partir de différentes sources de données. Nous n'avons pas eu recours à des méthodes d'analyse statistique multivariées en raison du manque de données cohérentes sur nos multiples échelles spatiales et temporelles, ni à des techniques de modélisation de l'usage des terres en raison du manque ou de l'hétérogénéité des données disponibles pour valider des modèles dans ces contextes extrêmement dynamiques.

L'analyse des systèmes de production agricole a permis de caractériser différents types d'agriculteurs et d'enquêter sur leur processus de décision et leur capacité à innover en relation avec la structure et le fonctionnement de leur ferme. J'ai réalisé une analyse statistique multivariée pour produire une typologie structurelle avec des données tirées d'entretiens individuels avec des représentants de chaque type de ferme identifiée. L'approche qualitative multidimensionnelle des ressources et contraintes techniques, sociales et économiques des ménages a constitué un ajout précieux pour définir des typologies fonctionnelles de fermes pour les hautes terres du nord-ouest du Cambodge. Néanmoins, il s'agit là d'une représentation instantanée de la diversité des fermes à un moment donné. La période de validité de la typologie des fermes est prolongée par la combinaison de variables lentes et rapides. Dans un contexte de croissance économique rapide comme au Cambodge, il était important de sélectionner avec soin les variables lentes pertinentes pour la typologie en utilisant des connaissances expertes en matière d'innovation. Cette typologie peut servir de référence pour les études longitudinales à venir.

Le jeu de simulation RADA a permis de mieux comprendre les décisions des agriculteurs en les plaçant virtuellement en situation de décision. Les processus décisionnels ont été étudiés en temps réel à l'aide du jeu de rôle. Le jeu a révélé comment les agriculteurs mobilisent leur réseau social pour adapter et adopter les techniques de l'AC. Il a montré l'importance des prestations de service fournies par le projet (semoir pour le semis direct), qui ont permis de lancer et d'entretenir la dynamique d'innovation. La triangulation des résultats des sessions de jeu successives a progressivement amélioré notre compréhension des contextes d'innovation et a permis de démêler une réalité complexe. Cependant, cette approche de simulation participative a rencontré certaines limites, car le jeu n'a impliqué qu'un seul groupe de joueurs/agriculteurs dans chaque village. Augmenter le nombre de sessions de jeu améliorerait certainement la crédibilité scientifique, mais aurait aussi pour effet d'augmenter les exigences financières, et pourrait créer une fatigue de recherche dans les villages cibles. Traduire le jeu en une pièce de théâtre participative peut permettre d'impliquer un public plus large, au-delà des agriculteurs, et élargir la participation au village tout entier dans l'exploration collective de voies d'intensification durable, par exemple via la fourniture de services d'AC, l'établissement de pâturages améliorés ou de cultures de couverture permanentes dans les vergers.

Dans cette thèse, et plus généralement dans le domaine du développement agricole, les agriculteurs sont au cœur du changement. Ainsi, le ménage est la principale unité d'analyse même si, dans le contexte d'une agriculture de marché, les décisions individuelles sont de plus en plus influencées par les conditions économiques et les politiques à l'échelle mondiale. Mon étude portait essentiellement sur la décision des agriculteurs, qui est influencée par les opportunités économiques, en tenant compte des risques et de la capacité d'adaptation des fermes. Bien qu'une telle compréhension soit nécessaire, elle peut ne pas suffire à résoudre les problèmes agricoles actuels, notamment dans un contexte généralisé de dégradation des terres et de baisse de la productivité, et de risques accrus liés aux fluctuations des prix et aux aléas climatiques.

Même organisés en coopératives, les agriculteurs doivent faire face à un nombre croissant d'interlocuteurs au sein des filières : commerçants, fournisseurs d'intrants, usines de transformation et institutions de micro-crédit. Dans un contexte de mondialisation, les systèmes de production agricole ont rapidement évolué pour devenir plus complexes alors que les agriculteurs devenaient de plus en plus individualistes. Hors, l'émergence des filières agroécologiques doit nécessairement s'accompagner d'actions collectives, de plates-formes de communication impliquant les différentes parties prenantes dans des échanges et des négociations conduisant à des formes de consensus sur les conduites à tenir. Ces plateformes d'innovation transforment le rôle des agriculteurs de simples adoptants à co-concepteurs d'innovations et celui des chercheurs et techniciens de créateur ou prescripteur à celui de facilitateur du processus de co-conception. Une telle approche implique toutes les parties prenantes dans un processus d'apprentissage collectif visant à accompagner la transition agroécologique vers une intensification durable des modes de production agricole.

Table of Contents

List of Figures

List of Tables

List of Appendixes

Chapter 1

General introduction

1.1 Land use changes driven by agricultural expansion and intensification in Southeast Asia

Over the past decades, most Southeast Asian countries underwent an agrarian transition that we define following Müller *et al.*, (2014) and Kull *et al.*, (2018) as a regime shift from a subsistence-based to a commodity-based agriculture associated with the opening of the region to the market economy. Many authors have described this profound transformation of the socio-ecological systems associated with market globalization (De Koninck, 2011; Macours and Swinnen, 2002). In Southeast Asia, the “green revolution”, through increased outputs from commercial crops, largely drove the shift from a society characterized by accumulation in agriculture to a society in which accumulation occurs through industrial development. In the alluvial deltas, cradle of the rice civilization, investments in landscape engineering (i.e., irrigation and drainage systems) associated with the techniques of the green revolution (i.e. high yielding varieties, energy-intensive production with agro-chemical inputs and mechanization) led to the annual production of two to three cycles of high yielding varieties. Land clearing in the forested uplands turned the subsistent into commercial farming with industrial plantations of rubber, palm oil, eucalyptus, etc. Through interventionist policies in agriculture (i.e. support to high yielding variety seeds and chemical inputs), governments planned to generate agricultural surpluses while reducing poverty in the countryside and accelerating the integration of their national economies into the global market (Castella, 2012; De Koninck, 2011). Thanks to massive expansion of farmland, crop intensification policies helped avoid modifying agrarian structures through social reforms. The combined mechanisms of agricultural intensification and expansion led to exceptional production growth in in Asia as compared to other continents (Figure 1).

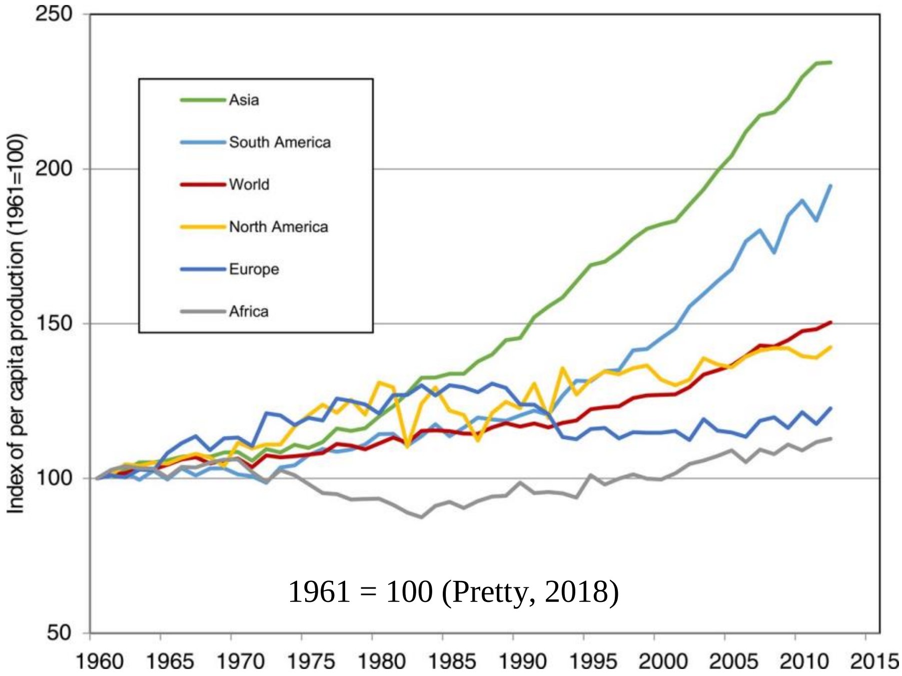


Figure 1. Global per capita agricultural production

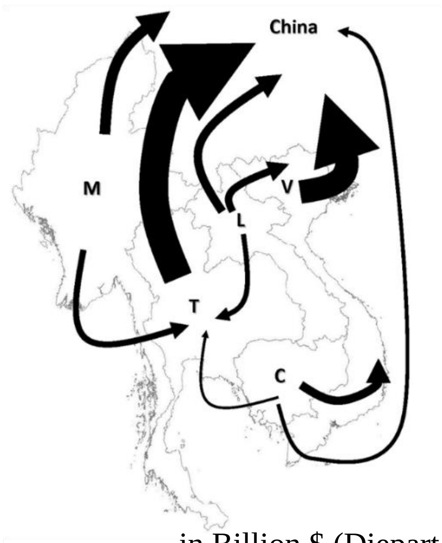
The pathways of these agrarian transitions differed between countries and regions depending on the time it occurred as well as their political and economic contexts (Bernstein, 1996). In the industrialized countries, intensification and mechanization of agricultural production were key instruments in meeting the demand for food and for further industrialization (Byres, 1977). In agrarian countries, the States used agricultural land pioneering as a tool to control frontier territories. Such was the case in the Philippines at the beginning of the 20th century, in Indonesia, especially since the 1950s, in Thailand in the 1960s, in Malaysia since its independence, in Vietnam over the last thirty-five years and more recently in Laos, Cambodia and Myanmar (De Koninck, 2011). Agricultural expansion through redistribution of populations from the geopolitical centers to the peripheries was also used for diluting the presence of ethnic minorities.

In Southeast Asia, market liberalization became an instrument for regional and global integration (Alagappa, 1995), i.e. through increased investments in the agroindustry sector in those countries with fast growing economies such as Thailand. In the early 2000s, the blossoming agroindustry increased the demand for cereals, tubers and fiber raw materials in the entire region. Commodity crops such as maize and cassava were more profitable than upland rice or pulse crops, among other species, produced under traditional slash and burn farming, so rotational systems with long fallow times quickly shifted to permanent cultivation once access to production factors and the market was provided. This shift from extensive to intensive cropping systems was commonly associated with soil tillage, herbicide use, and short (or no) fallow time. In addition, high profitability drove the continuous agricultural colonization to the forestlands. Colonization is mostly observed in the frontier areas, where complex land use dynamics are framed by insecure land tenure, weak law enforcement, inflow of migration, and strong market access (Geiger, 2008; Taylor, 2016). The rush to land for farming without complying with the existing national development plans undermined the sustainable development of smallholder farming systems in multiple ways:

- The forest ecosystems and biodiversity are all lost as the clearance is done as massively and quickly as possible without regulations.
- The pioneer farmers who are mostly the poorest of the poor risk their lives through landmines and malaria to appropriate the land, which may be later sold to wealthier farmers for a higher price.
- The agricultural expansion is necessary as the performance of the cropping systems relies on the exploitation of the initial soil fertility of cleared land until it is exhausted; requiring opening new land into marginal territories until the frontier is reached.

This rapid agricultural colonization is driven by impressive economic growth in the region and international trade with China (Ingalls *et al.*, 2018 and Figure 2), which increase exponentially the demand for raw agricultural products to feed the growing agro-industry. Those agro-industries favor economies of scale by promoting monocropping, thus specializing their industrial processes on single commodities, such as maize or cassava. Providing farmers with seeds, herbicides, and tillage services is sufficient to start the process. Road infrastructure usually follows agricultural expansion, often supported by the traders who subsidize the construction of feeder roads through lowered purchase prices of agricultural products (Phaipasith, 2016). In fragile ecosystems as in the North of Laos, Vietnam and Thailand with steep slopes and erosive soils, the conventional practices of soil tillage and/or slash and burn with short or no fallow times induces soil erosion and land degradation. Specializing in the production of a single crop is highly risky in the sense that farmers become indebted to keep up with increasing production costs and increasingly bet against the uncertainties of weather and the market.

Thailand to China	77.5
Viet Nam to China	29.9
Thailand to Viet Nam	6.6
Myanmar to China	5.4
Cambodia to Viet Nam	3.7
Laos to China	3.4
Laos to Viet Nam	3.0
Viet Nam to Thailand	2.7
Myanmar to Thailand	1.9
Laos to Thailand	1.1
Cambodia to China	0.9
Cambodia to Thailand	0.8
Myanmar to Viet Nam	0.8



in Billion $ (Diepart et al., 2017)

Figure 2: The trade flow of agricultural commodities 2005-2015

At the initial stage of the crop-boom process, when soils are still productive and prices are high and stable, the successes of the early adopters convince other farmers to engage in the same production systems creating much enthusiasm and leading to exponential production curves. The boom crop expands rapidly through massive adoption by smallholder farms through an imitative process, thanks to its high profitability. The downsides are quick to follow. Once the soils are exhausted, farmers attempt to maintain their levels of production by using expensive fertilizers and therefore increase their production costs or expand their production to marginal lands (i.e. with steeper slopes, stones, etc.). Their risk of failure increases as a result. Former shifting cultivators are usually not aware of these drawbacks and are not well prepared to tackle them. As a result, they easily fall into indebtedness with a crop failure in only a few years. Together with costly family shocks (i.e., illness, high cost events such as marriage or funerals, etc.), they are forced to sell their land and become wage laborers, mostly by migration to wealthier neighboring countries such as Thailand. The better-off minority manages to adapt to the bust phase of the crop boom not because they anticipated it, but because they accumulated enough capital during the previous phase, which they can use to cope with cash flow shortages and thus invest in the production of new commodities, such as orchards and intensive vegetable or cattle production. Along with this process, land is consolidated in the hands of the better-off minority. Consequently, social differentiation increases; the landscape becomes more fragile, fulfilling less ecological functions and providing less ecosystem services.

Knowing the negative consequences of crop booms, why are boom-bust cycles still occurring across Southeast Asia?

One reason for the persistence of crop booms observed in forest frontiers is that these commodities are an instrument of land appropriation for both smallholder farmers and agribusinesses. As land tenure is not secured in most of the upland areas, crops like maize and cassava that do not require high investments or specific technical knowledge from the farmers are rapidly adapted to secure land tenure with minimum economic or labor investments. All actors, i.e. poor pioneers, local authorities, traders, and better-off farmers, are in an opportunistic strategy to grab the economic benefits while externalizing the environmental costs. Another reason is the regional economic integration in which the exportation and trade balance play a key role in national economic growth. The countries with emergent economies, such as Cambodia, Laos PDR, and Myanmar are targeted by the agro-industry companies to produce commodity crops to export as raw or semi-processed materials to China via Thailand and Vietnam (Ingalls et al., 2018a).

In the context of the recent neo-liberalization of the global South, policy-makers have developed a positive discourse on the role of agro-industry investments to ‘modernize’ agriculture. Private investments, contract farming and economic concessions are seen as instruments of modernization that benefit the industry by supplying highly demanded raw materials that will ultimately lift the poor farming communities out of poverty. Under the agricultural modernization policies, the Government needs these large-scale private companies to boost agriculture, which incentivizes the development of commodity crops.

During the last decade, agricultural expansion and intensification have been increasingly driven by private investments (Figure 3) under a turning land to capital policy (Baird, 2011 and Ingalls *et al.*, 2018). The main idea behind this concept is that private investors will bring in new technologies that will allow farmers to overcome those repeated problems which are due to their unsustainable cropping practices. However, in most cases investors privilege a rapid return on investment and do not care much about the sustainable management of the natural resource base. The intensive cropping practices they introduce are often more destructive to the environment than the ones used by smallholders. The investors usually go for ‘low hanging fruits’ and thus tend to repeat boom and bust cycles in successive locations, moving to the next pioneer front, once the soil fertility capital from former forested land is exhausted instead of turning to sustainable production practices that would be more demanding in terms of social reforms and landscape restoration.

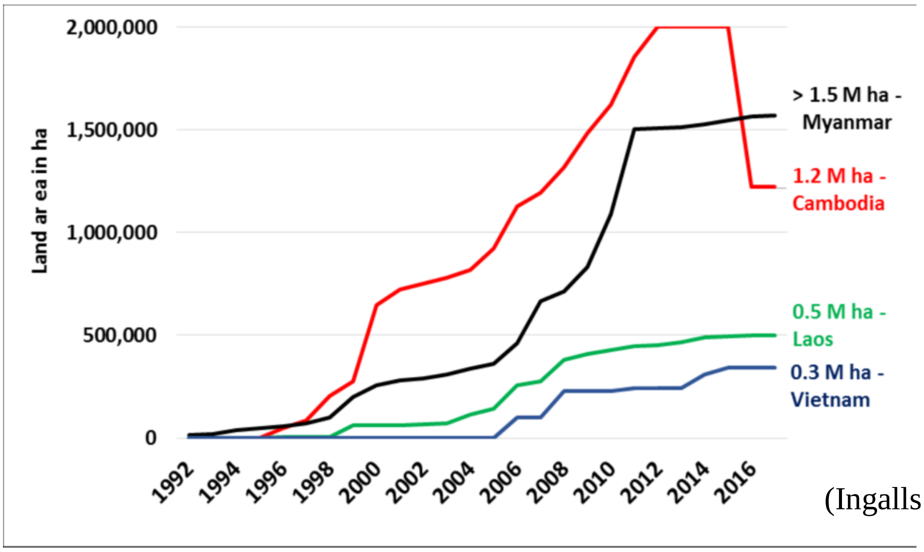


Figure 3: Evolution of land area granted as agro-industrial concessions

For instance, the boom cycles of hybrid maize moved from Thailand to Vietnam, then to Laos, Cambodia and currently to Myanmar. Within each country, the boom cycles of hybrid maize continue to move from place to place (Castella et al., 2016; Cramb et al., 2017). With limited road access and information sharing, the lessons learned in each location and negative experiences of land degradation and indebtedness are not shared, or not properly considered by actors involved in the same process in the next location.

How can we break the vicious cycle of boom-bust and promote sustainable farming systems in healthy landscapes?

The gradual commodification of agriculture contributed to the socioeconomic development of land frontiers through a combined process of agricultural expansion and intensification. However, massive forest and land degradation came along with this so-called modernization of agriculture and resulted in profound changes in landscapes and livelihoods (Hettig et al., 2016; Hurni et al., 2017; Nguyen et al., 2015; Vongvisouk et al., 2016). Pathways towards sustainable development are now actively sought following two successive periods of dramatic land use change: (i) pioneer fronts driven by the objective to assert State control over marginal territories through agricultural expansion, and (ii) commodification of agriculture through private land deals and intensification of agricultural production.

What would an alternative model of upland agriculture look like? Which pathways towards more desirable landscapes and livelihoods could be envisaged?

This PhD research intends to address these core questions.

1.2 Exploring pathways towards sustainable intensification of agriculture: from development challenges to research questions

Sustainable intensification of agriculture requires balancing the socioeconomic benefits with the integrity of the agroecosystem. Sustainable intensification gathers all practices that help maximize the production (of grain, tuber, or fiber) or economic return per unit of land and per year without undermining the productive potentialities of the cultivated agroecosystems for future generations of farmers. Sustainable agricultural development and natural resource management are high on the international agenda as they are central to the achievement of the Sustainable Development Goals (SDGs) supported by the United Nations (Pretty, 2018). Redesigning a new model of agriculture after the destructive pioneer front wave and with most of the same actors as those involved in intensive monocropping is quite challenging. The socioeconomic environment may not be supportive of such a profound transformation. An increasing number of private companies still promote technology packages including hybrid seeds, pesticides, mineral fertilizers, mechanized tillage, etc. National policies for agricultural development have also considerably paved the way for boom crops. The absence or very limited promotion of agricultural development options that are outside the boom crop realm leave farmers without convincing alternatives. Duped into 'least effort logics', farmers just pick one or more of these readily available technologies to solve their short-term problems without receiving any warning from other stakeholders concerning the possible long-term adverse impacts until they emerge.

Meanwhile, international institutions such as FAO, CIRAD, ICRAF and other development agencies for sustainable intensification promote a range of alternative practices such as conservation agriculture (Kassam and Friedrich, 2012), agroforestry, integrated farming, IPM, etc. These practices can be grouped under the term 'agroecology', and aim to achieve three main interlinked objectives: (i) increasing the performances / productivity of the cropping systems, (ii) preserving the fertility of the land and biodiversity and (iii) maintaining the resilience of the agricultural production systems to natural and economic fluctuations through diversified income sources. Nevertheless, the promotion of conservation practices for the farmers who cultivate in fragile upland agroecosystems encounter a number of constraints. These are:

- Biophysical constraints of rough terrains and steep slopes that constrain the design of economically viable technical options based on the appropriate scale machineries to offset the out-migration of rural labor force;
- Socioeconomic conditions are poor, especially for ethnic minorities, and investment capacity is low in remote upland areas with limited access to infrastructures (i.e. few roads mostly of poor quality), access to government services (i.e. education, subsidized credit), and access to markets for selling products and buying inputs;

- The promotion of single technological packages by private companies is widespread and farmers usually pick short-term over long-term solutions to their immediate problems. Besides, connections between farmers – service providers – retailers/dealers of agricultural machinery are locked in the mainstream socioecological regime that supports high input use; and
- So far, payment for environmental services is not a convincing option as either the services provided are not sufficient or difficult to measure transparently or the payment is too low compared with income generated from tillage-based farming systems. Generally, the producers support the costs of the initial investment in landscape restoration using conservation practices, i.e. yield decreases during the first years, additional labor and cost, sourcing or producing new inputs such as biopesticides. However, they do not receive any premium on the price for their agroecological products; the extra costs for good environmental practices are not visible to the consumers.

Agricultural researchers who promote agroecology face a number of challenges in a context of rapid changes: loose territorial governance, competing interests along value chains, and complex socioeconomic environments. They need to work at multiple scales, from multiple disciplinary perspectives, combining participatory diagnosis and co-design approaches to remain relevant despite the rapidly changing land uses and context specific with broad scale implications for sustainable intensification. Previous research has identified windows of opportunity for intervention along the boom-bust cycle (Castella et al., 2016; Ornetsmüller et al., 2018). The promotion of alternatives to boom crops should intervene before the beginning of the boom, when farmers are still engaged in subsistence farming or after the bust phase once farmers are fully aware of the negative effects of intensive monocropping on land degradation. Also, the innovations proposed during the boom phase of the cycle are mostly not economically attractive enough compared to conventional practices. So should we, as researchers, allow the crop boom go on until it self-defeats and do nothing? Certainly not. We should engage as soon as possible with all stakeholders in co-designing pathways to sustainable intensification. Researchers should become active players of an agroecology transition through collective learning with farming communities and all actors of the value chains and the territories of production. All actors should discuss and negotiate this in order to come up with their own context specific and locally adapted pathways towards sustainable intensification.

Market price and demand are key factors influencing farmers' decision making for their crop choices and practices in particular for commodity crops. Farmers usually opt for the high return crops they identify and prioritize using a combination of technical, environmental, and economic dimensions influencing temporal and spatial demand and supply elasticities. Technological development, i.e. in agrochemical inputs and machineries, as well as climatic hazards and natural disasters also impact the production contexts and supply chains (Gilbert and Morgan, 2010), while changes in consumer habits affect the demand side. The sudden changes in trade policies (Christiaensen, 2009) and financial speculations (Robles, Torero and Braun, 2009 and Inter-agency Report, 2011) also significantly influence commodity prices. Forecasting models for agricultural commodity prices remain largely uncertain due to political influences (Rezitis et al., 2015). Changes in political economy and trade at the international level definitely influence farm gate prices. As these global economic dimensions are beyond the framework and mandate of the development operators, they develop bottom-up approaches to increase the resilience of local stakeholders to unpredictable events and economic megatrends. They also empower farmer communities to advocate and influence political decisions towards sustainable agricultural production.

Despite higher-level influence on their decision-making, farmers are key agents of change, essentially because they have a direct stake in land-based practices as their lives depend on them. This PhD research examines farmers' decision-making as a leverage point towards (i) sustainable intensification from plot to landscape, (ii) bottom-up policy influencing strategy, and (iii) negotiation of alternative development pathways with market actors. Understanding the diversity of farming systems and their decision-making processes is a prerequisite of any development intervention, since individual decisions made on which crop to grow and how to manage cultivation impact agricultural development at higher levels. In addition, we may change intensification pathways by influencing farmers' decisions and other actors along the value chain (Christiansen et al., 2018).

In many decision models, farmers are expected to maximize economic benefits from limited resources, leading to linear programming and optimization techniques. Farmers' strategies tend to optimize farm activities accordingly to the capital, knowledge and anticipated risks from external factors i.e. rainfall and market forces. The relations between farm structures and functions are also investigated as farm households with similar characteristics in terms of livelihood assets, activities and constraints are expected to develop similar strategies. Farm typologies commonly use surveys of household samples and cover a large range of parameters (Cochet, 2015). Farming system approaches are then used to characterize the decision-making processes of different groups of farmers clustered into a farm typology. The decision models are based on multivariate analysis in order to understand which parameters contribute to the decisions on any given land use or innovation (Rubiano, 2001). Recognizing that a large number of constraints, i.e. psychological, socioeconomic, institutional, environmental and political bind the rationality of the decision maker, decision models based on bounded rationality (Cristofaro, 2017; Malanson et al., 2014) have also been developed to better understand farmers' decision making and to explore the diversity of farming systems (Tittonell et al., 2010).

Furthermore, participatory approaches, such as agent-based models with role play games (Barreteau et al., 2013; Etienne, 2014), are used to engage all stakeholders in addressing the issues of land management and innovation adoption at multiple scales. Researchers co-design the decision model with other stakeholders and help it evolve according to scenarios or circumstances that could result from a mutual consensus on sharing of common natural resources i.e. water and grazing areas. This approach is also used to support collective learning on managing the commons and exploring trade-offs between conflicting objectives associated with different decision models. To have an impact at the landscape level, all actors from farmers to policy makers, and not only landowners, should be involved.

1.3 NW Uplands of Cambodia as a case

The NW Uplands of Cambodia capture some of the land use dynamics widely observed throughout the region. Our study area was mostly covered with dense forest until the end of the 1990s (Figure 4). It was the last stronghold of former Khmer Rouge fighting with the Cambodian Government until the 1998 peace agreement. At that time the Khmer Rouge reintegrated the Government and the Cambodian civil war officially ended. After allocation of forestlands to demobilized soldiers as part of the peace accords, the areas became one of the last forest frontiers in the region. Farmers engaged in successive boom-bust cycles of maize, followed by cassava, and mango.

The conversion from forest to agricultural lands was massive and rapid, driven by two successive push-pull factors. First, the vast available forests attracted a massive flow of in-migration from the neighboring lowland areas, where the land was fully saturated. The land scarcity in the alluvial plains pushed the land-poor farmers to appropriate land in peripheral upland areas with minimal cost. Secondly, while the arrival of migrants continued, the increasing land price, thanks to a high-income farming generation, pushed the first wave of migrants to expand or sell their newly cleared land and appropriate or buy forestland at lower prices further away, along the forest frontiers or in the hills and mountains. Improved market access and the introduction of hybrid maize seeds were the main driving forces behind the maize boom that occurred in Cambodia between 2006 and 2012.

In 2009, concerned about the disastrous impacts of the maize bust, the Ministry of Agriculture, Forestry and Fisheries initiated a research and development program on conservation agriculture (CA) with technical support from CIRAD. Its objective was to design maize-based cropping practices as an alternative to intensive monocropping systems that had spread rapidly since 2006. The program developed pilot extension activities in the study areas based on two approaches, first with a subsidized package of CA practices from 2010 to 2012, and second with a contracted services provision and free technical advice from 2013 onwards. The proposed technical options resulted from a co-design process (Husson et al., 2016). While they responded to the three objectives of sustainable intensification, the proposed practices were not widely adopted by the farmers even with a subsidized package because its economic benefits were lower than with the conventional practices based on soil tillage and herbicides. In addition, the price paid to farmers was the same for maize produced under CA and non-CA techniques.

Farmers’ interest for CA maize increased during the bust phase of the cycle, but the response of a majority of farmers to the maize yield decline was to switch to another boom crop, cassava, instead of adopting maize-based CA practices. The co-design process of CA cropping practices was somehow running behind the rapid land use transformations. By the time cassava-based CA practices become available after a co-design period followed by pilot validation, the farmers may have already shifted to another boom crop, mango. The research community is challenged by the speed of the changes in land use and land cover and has to adapt its methods, as well as proposed technical options and intervention approaches, to the specific context of the NW Uplands of Cambodia. On the other hand, the stories of boom crops are repeating in time and space all across Southeast Asia and the lessons learnt from our study site in NW Cambodia will be useful for farmers undergoing similar changes. Ultimately, the study aims at breaking the boom-bust curse by co-designing relevant research methods and intervention mechanisms with local stakeholders aiming towards sustainable intensification both at farm and landscape levels.

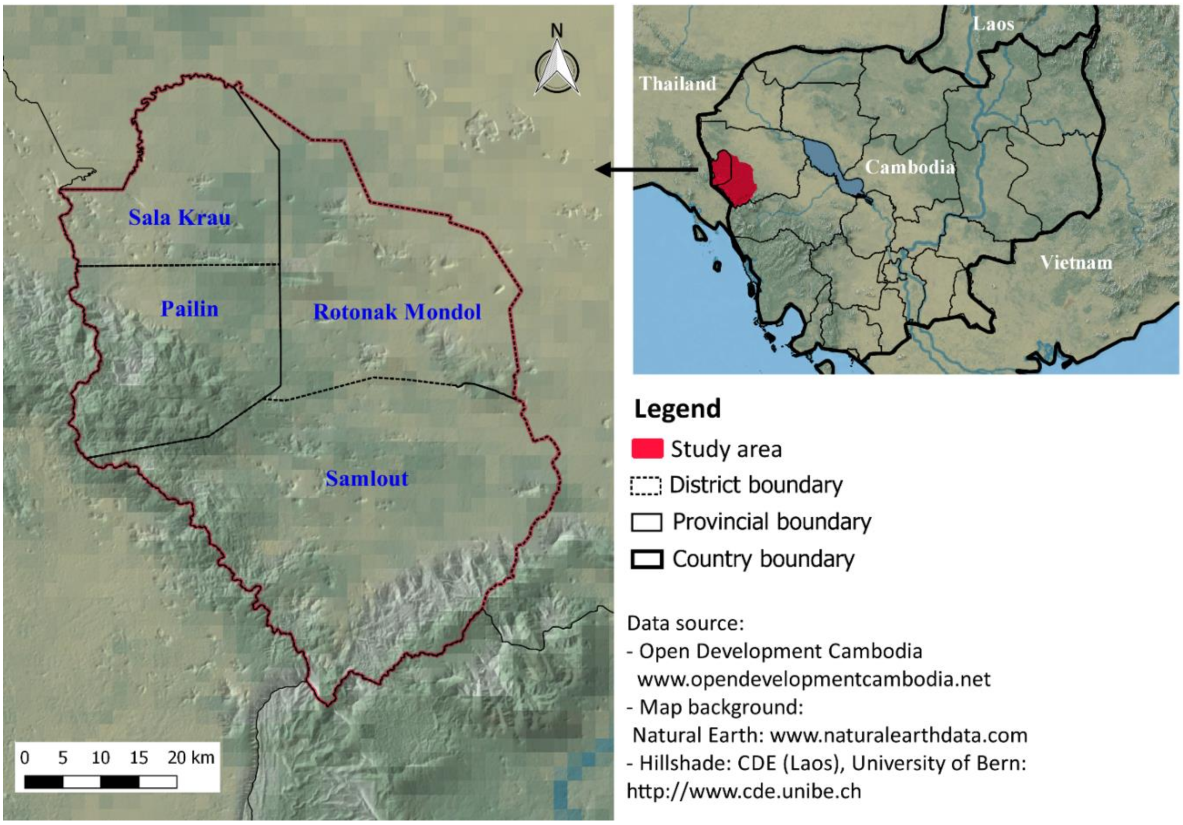


Figure 4. Location of the study area in Cambodia.

1.4 Goals, objectives and overview of the dissertation

The goals of this thesis are:

- To understand the complex interactions of factors that contribute to farmers' decision making processes in a context of rapid land use changes; and
- To support the sustainable intensification of upland agriculture through the definition of appropriate intervention mechanisms

This research addresses three specific objectives:

- To analyze the patterns and pace of land use and land cover changes (LUCC) in NW Cambodia over the recent decades and investigate their drivers at multiple scales;
- To characterize the current diversity of farming systems, how it was built up in time and their specific responses to changing socio-ecological environments; and
- To investigate farmers' decision-making process and explore relevant intervention mechanisms through participatory simulations.

1. To achieve these goals, we combined three different approaches to investigate farmers' decision-making processes (Figure 5 and Table 1). Land use change analysis based on chronological series of remote sensing data allows characterizing the speed and extent of changes. Converging evidence at multiple scales and from the perspective of multiple stakeholders was confirmed by quantitative and qualitative information from various sources, i.e. remote sensing data, socioeconomic data, and surveys of key resource persons.

2. The diversity of land uses and land use changes reflects a diversity of farming systems which mobilize different practices and strategies to reach their goals and make decisions based on their specific resources and constraints, both internal and external. We use a farming system approach to understand the decisions made at farm and plot scales, characterize farm diversity and trajectories at the regional level and assess their performances and capacity to innovate through a combination of structural and functional typologies based on quantitative and qualitative surveys.

3. Lastly, we used a simulation game with villagers to confirm and validate our understanding of farmers' decisions from plot to village scale. We then used this game with representative farmers from different farm types to explore scenarios on the land use changes and innovation systems. We could thus identify intervention mechanisms to engage with farming communities into transformative pathways with appropriate intervention mechanisms towards sustainable intensification.

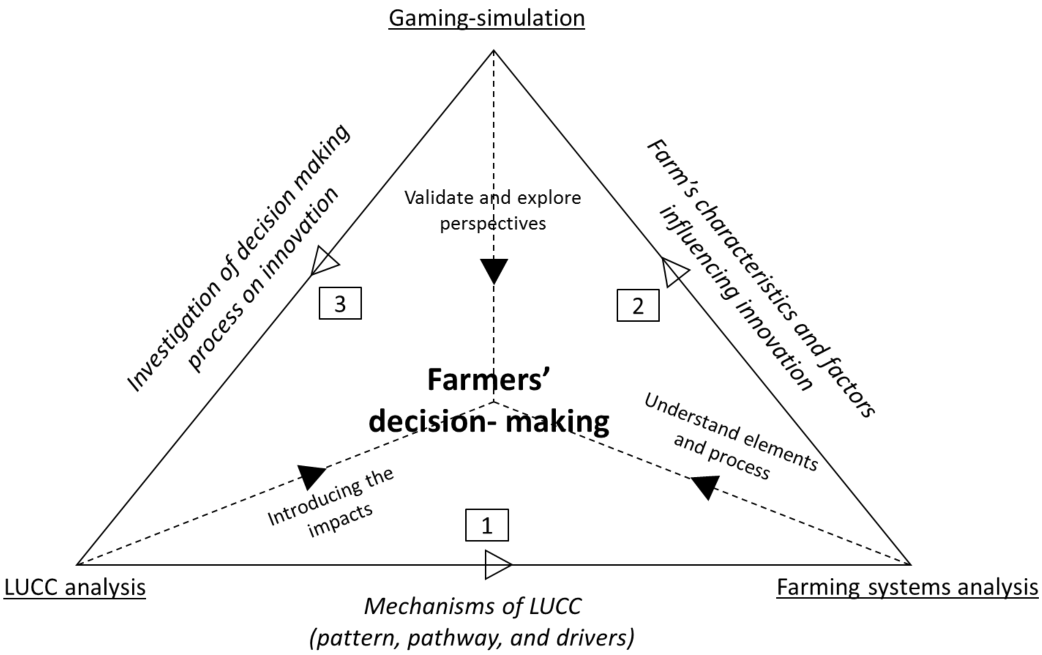


Figure 5: Methodological framework

Table 1: Methods for sampling and data collection

Obj.	Scales	Samples	Information	Data	
				Field data	Secondary data
Obj. 1	- Regional	- 4 districts in the pioneer front of the Northwestern Uplands of Cambodia	- Demography, In-migration, Land tenure systems, Agrarian history, Land use history, political economy, institutions…etc.	- 19 semi instructed interviews, 3/2016 - 5 focus groups discussions with 48 participants, 4/2016 - Ground truth survey, collected 1474 GPS points, 3-4/2016	- 6 Landsat images: 1976, 1997, 2002, 2006, 2010, and 2016 - Census 2008 - Communal database 2006-2016 - Agricultural data of PDA* - Previous studies
Obj. 2	- Inter-villages - Household groups Households	- 10 of all 38 villages in Rotonak Mondol District - 365 households sample for the household questionnaire survey - 95 of 365 households for in-depth interview	- Farm resources: livelihood assets, production systems and historical trajectories - Livelihoods activities and general constraints and strategies - Farmers' decision-making process on resources allocation and livelihood activities	- Household questionnaire survey, 1-4/2016 - In-depth interview of households, 1-4/2017	- Previous studies: 2010 feasibility study for CA* project - Village official database
Obj. 3	- Inter-villages - Village - Household group (CA and non-CA) - Plots (CA and non-CA)	- 165 CA project farmers (all available households) - 6 of 10 villages (3 CA and 3 Non-CA) - 48 farmers as players - CA plots and non-CA plots	- Reasons to experience, stop and continue the CA - Farm's decision-making process on the land uses and CA adoption - Farm's specific constraints and potentials for CA - Individual and collective perception on CA and supports - Economic performance CA and non-CA systems	- In-depth interviews of households, 1-4/2017 - Co-design role playing game (RADA* game), 12/2017 - Game workshop, 01/2018 - Following up survey with individual players, 01/2018	- CA project documents and reports

*Note: RADA: Resilient Agriculture through Co-Design of Agroecology pathways; CA: Conservation Agriculture, PDA: Provincial Department of Agriculture

This dissertation is organized in five chapters:

Chapter 1 (this section) is a general introduction of the thesis with background information on the challenges of sustainable intensification in former forest frontiers and research questions to address those challenges. The results are presented in the next three chapters, each corresponding to a specific objective of the thesis.

Chapter 2 focuses on understanding the drivers of deforestation and agricultural transformations. We present the patterns and drivers of LUCC based on a classification and quantification of LUCC, an explanation of proximate causes, underlying factors and their causal linkages. We investigate the underlying mechanisms of LUCC along the conceptual framework provided by Geist *et al.*, (2006). Landscape changes result from decisions made by individual land users.

Chapter 3 addresses the diversity of upland farming systems and their role in agricultural innovation systems. Moreover, it illustrates how each identified farm type built up in time and how their performances and strategies evolved. We analyze the influences of farm structures on their performances and capacity to innovate as well as their room for improvement and the possible leverage points for each farm type.

Chapter 4 investigates farmers' decision-making in relation with the adoption of conservation agriculture, based on the thorough understanding of characteristics and performances of each farm type. The gaming-simulation approach, named Resilient Agriculture through co-Design Agroecology Pathways (RADA), was co-designed with local stakeholders (Table 1). We report here the design process, followed by the results of the successive role-plays in CA and non-CA villages. We show how decisions made in the past influenced the current settings and how path dependency mechanisms constrain possible land use trajectories towards sustainable intensification. Finally, we investigate the conditions of adoption of CA techniques for farmers with different resource endowments, constraints and strategies, and draw lessons on how to support innovation processes such as CA in a context of rapid land use changes.

Chapter 5 puts the main results of the thesis into the larger question of how to support the broad scale adoption of agroecology practices and how to create an enabling environment for sustainable intensification at the regional scale. The perspectives for relevant research and possible impact pathways for sustainable development are also discussed.

Chapter 2

Understanding the drivers of deforestation and agricultural transformations in the Northwestern uplands of Cambodia

Abstract

At the end of the 1990s, the Northwestern uplands of Cambodia were one of the last forest frontiers of the country. In a region that was the last Khmer Rouge stronghold, the opening of former conflict zones after a peace agreement initiated a vast movement of agricultural colonization. This movement was economically triggered by high market demand for agricultural commodities such as maize and cassava and fueled by a massive flow of spontaneous in-migration of land-poor farmers from lowland regions around the entire country. Focused on four upland districts along a pioneer front of Northwestern Cambodia, we analyzed historical trajectories of land use/cover changes using a chronological series of Landsat data from 1976 to 2016. We identified key drivers of deforestation using demographic data and qualitative information from local actors and other relevant stakeholders. We found a 65 percent forest cover loss due to conversion by smallholders into agricultural land for maize and cassava cultivation over a period of 15 years. The underlying mechanisms of land use change were further investigated to understand the diversity of individual farm trajectories and decision-making processes in relation to land conversion. These elements of diagnosis are essential to engage farming communities in innovative land use systems and to develop sustainable alternatives to boom crops that have led to the current situation of land degradation and economic instability.

This chapter is based on the following research article:

Kong R., Diepart J.-C., Castella J.-C., Lestrelin G., Tivet F., Belmain E., Bégué A., 2019. Understanding the drivers of deforestation and agricultural transformations in the Northwestern uplands of Cambodia. *Applied Geography* 102, 84–98; https://doi.org/10.1016/j.apgeog.2018.12.006

2.1 Introduction

Tropical deforestation stands out as a key feature of global land use changes (Hansen et al., 2013) although the arguments advanced to explain it are usually far from conclusive (Lambin et al., 2001). The factors and pathways driving deforestation are indeed intricate and result from multiple factors, both local and regional, originating from different levels of organization and acting in various combinations in different locations (Geist and Lambin, 2002).

In Cambodia, deforestation is associated with both rapid economic growth and agricultural expansion (Diepart & Sem, 2015) reflecting the emergence of boom crops all across Southeast Asia (Hall, 2011). Recent waves of deforestation have been quantified and documented, although mainly in relation with the development of agro-industrial plantations granted as economic land concessions on state land (Davis, Yu, Rulli, Pichdara, & D'Odorico, 2015; Fella, Barua, Tamminen, & Hatcher, 2017). Little is known about other forms of forest conversion, particularly those produced by migrant smallholder farmers that are prevalent in the Northwestern corner of the kingdom. There, agricultural expansion into forested upland margins has led to the emergence of new agrarian systems mainly based on annual crops such as maize, cassava, peanut, and soybean. In Pailin and Battambang Provinces as a whole, the area of these crops increased six fold between 2001 and 2015, from 40,000ha to 250,000ha in 2015 (MAFF, 2001, 2015).

The region was the cradle of the Khmer Rouge (KR) uprising in the sixties and the rear base of their resistance against governmental forces in the eighties and nineties. In this region, the KR reintegration policy had designated new settlement and administrative areas in which KR soldiers were allowed to resettle and where their representatives were given responsibilities in land management. The subsequent allocation of forested land to demobilized soldiers and their families then marked the opening of the agricultural frontier, which created incentives for further migration (Diepart & Dupuis, 2014).

A first body of literature looking at agrarian changes in the region focuses on the political economy of land governance. It argues that land has emerged as common ground between a moving population and the combatant forces seeking to control them with a legitimized use of force (Pilgrim, Ngin, & Diepart, 2012). It also suggests that the struggles between KR and neoliberal modes of land control are central to state formation processes (Diepart & Dupuis, 2014).

A second body of knowledge examined the economics of boom crop production and the commercialization of smallholder agriculture. This literature argues that despite a quick increase in farm income and household assets in the early stages of the boom (Kem, 2017), agricultural expansion quickly made the farmers highly dependent on market fluctuations and generated negative impacts, including soil degradation and reductions in yield and crop profitability (Belfield, Martin, & Scott, 2013; Kong et al., 2016; Montgomery, Martin, Guppy, Wright, & Tighe, 2017).

However, the literature does not sufficiently capture the actual pathways of land use and land cover change (LUCC) in the Northwest and in particular the institutions and mechanisms that are involved in the changes. To shed light on these processes, we have developed a multi-scale analysis that examines agrarian change over the past 40 years in the upland areas of Battambang and Pailin Provinces. This paper endeavors three things. Firstly, we set the magnitude of land cover changes at the landscape level (covering four districts) using remote sensing technologies. Secondly, by drawing on secondary data, we identify the proximate causes and underlying factors that have driven land cover changes. Thirdly, based on primary data collected during fieldwork conducted in 2016 and 2017 in one specific district of the study area, we develop a graphic representation of LUCC mechanisms that allow for a detailed understanding of the interactions between the multiple drivers of changes along with the variations of these interactions across time and space.

2.2 Methodology

2.2.1 Framing the LUCC analysis: a multi-scale approach

Changes in land cover (biophysical attributes of the Earth’s surface) and land use (human intentions applied to these attributes) are complex and dynamic (Lambin et al., 2001). They are driven by a combination of factors in synergic interaction, acting at different scales and originating from different levels of organization in the social-ecological systems (Geist & Lambin, 2002; Turner & Meyer, 1994). Recent research has proposed moving beyond simplistic linear causation models of LUCC to include an empirically rooted understanding and interpretation of a large number of factors interacting at different temporal and spatial scales (Lambin et al., 2003).

To account for the change of land cover and land use observed in the Northwestern uplands of Cambodia, we have adapted the framework developed by Geist and Lambin (2002) as shown in Figure 6. We have used this framework as it clearly differentiates proximate causes operating at the local level and underlying forces which originate from regional or even global levels. Proximate (or direct) causes of land-use change constitute human activities or immediate actions that originate from intended land use and directly affect land cover, while underlying (or indirect, or root) driving forces are fundamental forces that underpin the more proximate causes of land-cover change (Lambin et al., 2003). Based on the literature review relevant to the agricultural expansion in the Northwest of Cambodia (Diepart and Sem, 2015; Diepart and Dupuis, 2014; Diepart and Sem, 2018; Montgomery et al., 2017; Touch et al., 2016, 2017), we identified three main categories of proximate causes: agricultural expansion and intensification, infrastructure development, and resources exploitation, and five main categories of underlying factors: political and institutional factors, economic factors, demographic factors, technological factors, and environmental factors (Figure 6). In addition, a number of elements of each proximate cause and underlying factor are defined as working hypothesis. The comprehensive analysis of LUCC therefore consists of investigating interactions as well as causal relations between proximate causes and underlying driving forces (Lambin et al., 2003).

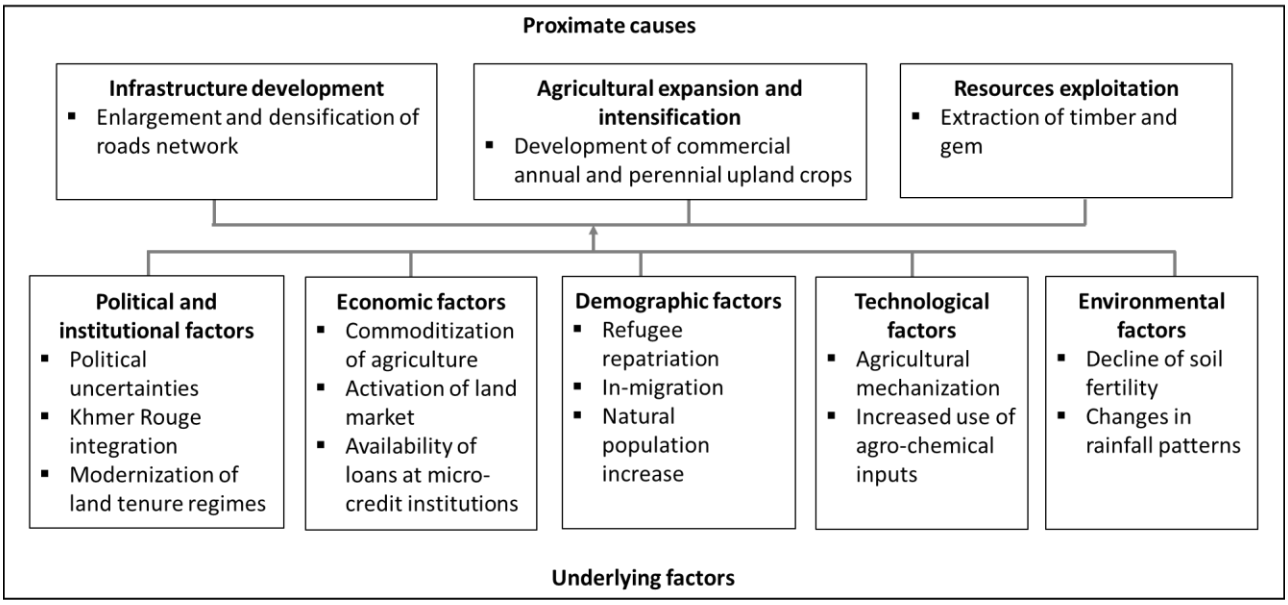


Figure 6: Conceptual framework of proximate causes and underlying factors of LUCC

NB: adapted from Geist & Lambin (2002)

2.2.2 Study site and data collection

The study area is located along a pioneer front in the Northwestern Cambodian uplands (Figure 7). The study area covers 3,200 km^2 with a total population of 158,000 people (PDP-BB, 2015; PDP-PL, 2015). It shares borders with Thailand in the west and was a KR stronghold until 1998. It includes four districts, namely Sala Krau and Pailin districts that belong to Pailin Province and Samlout and Rotonak Monol Districts that belong to Battambang Province.

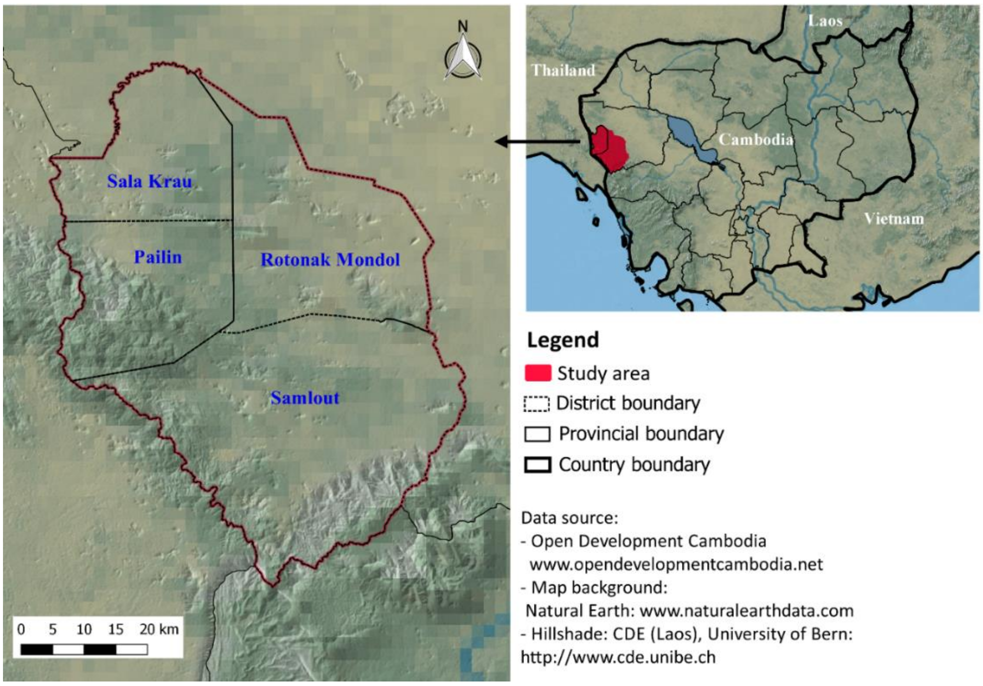


Figure 7: Location of the study area

Our analysis proceeded at two different levels along a three-step process (Table 2). We first conducted an analysis of land cover changes from 1976 to 2016 using remote sensing technologies for the entire study area. We then combined this spatial analysis of the nature and extent of land use/cover changes with field surveys to identify proximate causes and underlying factors of the observed historical changes. Finally, we carried out a detailed analysis of land use pathways only in Rotonak Mondol District, where several of the authors have been involved in field activities since 2010.

Table 2: Data collection and analysis across scales

<table>
<tr><th>Analyses</th><th>Scale</th><th>Input Data</th><th>Analytical processes</th><th>Outputs</th></tr>
<tr><td>Patterns of LUCC</td><td rowspan="2">Rotonak Mondol, Samlout, Pailin and Sala Krau Districts</td><td>Landsat scenes 1976, 1997, 2002, 2006, 2010, and 2016
Ground control points collected in 2016</td><td>Image pre-processing and classification
Accuracy assessment and image post-processing</td><td>LUC classification and maps
Quantification of land cover changes</td></tr>
<tr><td>Proximate causes and underlying factors of LUCC</td><td>Official statistics: census 2008 (NIS, 2009) and commune database 2006-2015 (NCDD, 2010; PDP-BB, 2015; PDP-PL, 2015)
Secondary sources 2001-2016 (PDA-BB, 2016; PDA-PL, 2016; JICA, 2001; Department of Geography, 2005; LICADHO, 2011; and PDLMUPC, 2014)</td><td>Categorization of drivers of land use changes
Sectoral analysis of proximate causes and underlying factors</td><td>Framework of proximate causes and underlying factors</td></tr>
<tr><td>Pathways of LUCC</td><td>Rotonak Mondol District</td><td>Individual interviews of resource persons and farmers in 2016
Focus group discussions with resource persons in 2016</td><td>Qualitative data analysis</td><td>Graphic representation of LUCC
Explanation of LUCC mechanisms</td></tr>
</table>

2.2.2.1 Land use and land cover classification

The LUCC analysis rests on a collection of Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) scenes acquired from the US Geological Survey site (http://earthexplorer.usgs.gov/) for six dates: 1976, 1997, 2002, 2006, 2010, and 2016 (Appendix 1). These dates were chosen based on the previous forest cover inventory at the country scale conducted by the Forestry Administration of the Ministry of Agriculture Forestry and Fisheries (Mekong Secretariat & River Commission, 1994; McKenney & Prom, 2002; Forestry Administration, 2010) and important historical milestones of LUCC identified in the literature (Diepart and Dupuis, 2014; Diepart and Sem, 2018; Pilgrim et al., 2012). Images were selected from relatively cloud-free acquisitions (<10 percent clouds) and at the same period of the year, during the Cambodian dry season from December to April.

The image pre-processing consisted of converting the Digital Number into Top-of-Atmosphere reflectance, resampling the 1976 MSS image at TM spatial resolution (from 60 m to 30 m), mosaicking the two Landsat scenes covering the study area, and sub-setting to encompass the study area. The classification process combined supervised classification (maximum likelihood algorithm) with ENVI 5.0 software and visual image interpretation with QGIS 2.14, applied to the six images.

Based on 1,474 ground control points randomly collected during a field survey in March 2016 and a false color composition (Near infrared for red, green for blue, red for green) of the 2016 image, we created by visual interpretation a ground data set made of polygons labeled into nine classes: water, artificial, paddy rice, annual upland crops, tree crops, grass, bush, degraded forest, and dense forest (Appendix 2). To build the ground data sets for the classification of the historical images (1976 to 2010), we established a look-up table between the observed land cover and the color composition of Landsat image based on the 2016 ground data set, and then used it as reference to photo-interpret and draw the polygons creating the data set for each previous date. The photo-interpretation was also verified with the retrospective interviews with local people referring to major areas of LUCC, and the same set of false color used in 2016 was applied to improve the visual interpretation.

Each ground data set was randomly split into training (50 percent) and validation (50 percent) data sets. Ten image layers were used in the classification process: five spectral bands (blue, green, red, near infrared, and short-wave infrared) except for the 1976 MSS image as only three (green, red, and near infrared) were available, two spectral indices (Normalized Difference Vegetation Index – NDVI, Normalized Difference Water Index – NDWI), and three texture indices (homogeneity, entropy and correlation). The NDVI and NDWI were calculated using respectively the equation [NDVI = (Near Infrared band – Red band)/(Near Infrared band + Red band)] developed by Rouse et al. (1974), and the equation [NDWI = (Near Infrared Band – Short Wave Infrared Band) / (Near Infrared Band + Short Wave Infrared Band)] developed by Gao (1996). The texture indices were derived from the grey level co-occurrence matrix (GLCM) (Haralick et al., 1973).

The accuracy assessment showed overall classification accuracies between 74 and 93 percent with Kappa coefficients between 0.73 and 0.92 respectively (Appendix 3). Finally, the land cover maps were post-processed by filters application, vectorization and LULC correction. The filters application was done in three steps: Sieve Classes (group min threshold: 2, number of neighbor: 4), Clump Classes (7x7), and Majority analysis (majority with 5x5).

2.2.2.2 Proximate causes and underlying factors of LUCC

Proximate causes and underlying factors of LUCC were first identified through the literature review and were pre-classified as presented in Figure 1, using the conceptual framework proposed by Geist & Lambin (2002). We subsequently used them as working hypothesis to be gradually checked and validated through triangulation with different datasets. The local expressions and implications of LUCC drivers were investigated through qualitative methods based on semi-structured interviews of resource persons. The respondents were witnesses of recent LUCC selected through snowball sampling process for their intimate knowledge of causes and factors of changes (Appendix 6). The information obtained through their singular stories and individual perceptions of local changes were then generalized during focus group discussions. These collective sessions gathered some of the individual respondents and additional key actors of LUCC identified during the individual interviews (Appendix 6). They provided a broader perspective on the drivers of LUCC at the district level. Then, in-depth interviews of 95 farmers selected through stratified random sampling allowed to quantify some of the information provided during the previous surveys such as i.e. yield decreases after a few years of monocropping or in-migration trends.

We also validated working hypotheses on land cover change by triangulating with official statistics derived from government databases. The expansion of the road network was quantified based on four different datasets: 2001 (MPWT and JICA, 2003), 2005 (MLMUPC, 2005), 2011 (LICADHO, 2011) and 2014 (PDLMUPC, 2014). We derived data on population mobility and migration from the demographic census of 1998 and 2008 and we extracted other relevant socio-economic data spanning the period 2006 to 2010 from the national commune database (NCDD, 2010) and 2011 to 2015 from the provincial commune database (PDP-BB, 2015; PDP-PL, 2015).

We obtained yearly data of cultivated area of upland crops for the period 2001-2016 at the Provincial Departments of Agriculture of Battambang and Pailin. Yet, the dataset was too fragmented (data not systematically available for each year and each location, or changing indicators over the years) to conduct a multivariate statistical analysis of interactions within and linkages between proximate causes and underlying factors in relation with the LUCC. Therefore, validation was mostly done during the focus group discussions (Appendix 6) that were conducted in all the five communes of Rotonak Mondol District. Once an agreement was reached among participants on the list of proximate cause and underlying factors of LUCC, they were asked to rank the level of influence of these causes and factors on observed LUCC in their commune as weak, medium, or strong. These qualitative assessments were finally used to estimate the strength of the relations between causes and factors and their impacts on LUCC in the study area.

We also used the different data described above to develop a spatial representation of the mechanisms of interaction between causes and factors ‘on the ground’ (i.e. territorial dynamics such as road expansion, land allocation along the roads, etc.) that led to the observed LUCC from remote sensing in our study site. The chorematic representation of territorial dynamics, originally developed by Brunet (1980), has been used on multiple topics in the French geography tradition. These graphic abstractions or models highlight the territorial structures and processes more than the element's exact location, as practiced by conventional mapping. While a map is a representation of a geographic space at a point in time, the chorem seeks to understand how it has been built up over time. This involves an analytical process, which begins with establishing the relationship between land use transformations and its drivers on the ground. These relationships are social constructed; they are identified as socio-territorial logics by resource persons interviewed individually and confirmed collectively during focus group discussions. Because of delays in the design work, the graphic representation of LUCC (Figure 14) could not be validated by the group that originally contributed the local knowledge. It was validated by the experts who worked for many years in the area, some of them being co-authors of the manuscript.

2.3 Results

2.3.1 Land use/cover change analysis

The most remarkable LUCC was observed between 1997 and 2006 (Figure 8). Total forest cover (dense and degraded forestland) remained almost unchanged accounting for about 90 percent of the area between 1976 and 1997. However, around 13 percent of the dense forest area was converted to degraded forestland. During the following 20-year period (1997-2016), forest cover reduced dramatically, with only 25 percent remaining in 2016, and with a particular emphasis along the main roads. The 65 percent of forest cover loss occurred primarily between 2006 and 2016.

It appears obvious that the forest cover was lost to agricultural land (Figure 8 and Figure 9). Agricultural land increased tremendously from 1 percent in 1997 to 61 percent in 2016 with most of the conversion taking place between 2006 and 2016. Forest conversion occurred following two main pioneer fronts: one started from the Northwestern part of Pailin Province bordering with Thailand and another one from the Northeast neighboring districts with densely populated lowlands. Forest conversion was relatively more intensive and homogenous in Pailin, especially from 2002 to 2010. In 2016, the area looked fully saturated with the remaining homogenous forest cover in the South and Southwest, which was declared a protected area in 1993 (Royal Government of Cambodia, 1993) and a few spots scattered in the area which were not very suitable for agriculture due to steep slopes and rough terrain.

The 61 percent of agricultural land in 2016 (208,163 ha) is constituted of around 80 percent annual upland crops, about 10 percent of tree crops and 10 percent of paddy rice. Annual upland crops expanded rapidly to constitute the single most important agricultural land use since 2002, meaning that the conversion of forest land was undeniably for annual upland crops (especially maize and cassava). Paddy rice area also increased noticeably between 2010 and 2016 but at a slower pace than annual upland crops. Paddy rice remains spatially fragmented due to its need for hydromorphic conditions. Tree crops (i.e. rubber, longan and mango) emerged as an important land use in 2016. Overall, the large areas of tree crops and annual upland crops were developed mainly on dense forest (54 percent) and degraded forest (40 percent) while paddy rice was developed on degraded forest (53 percent) and bush (24 percent) (Appendix 4).

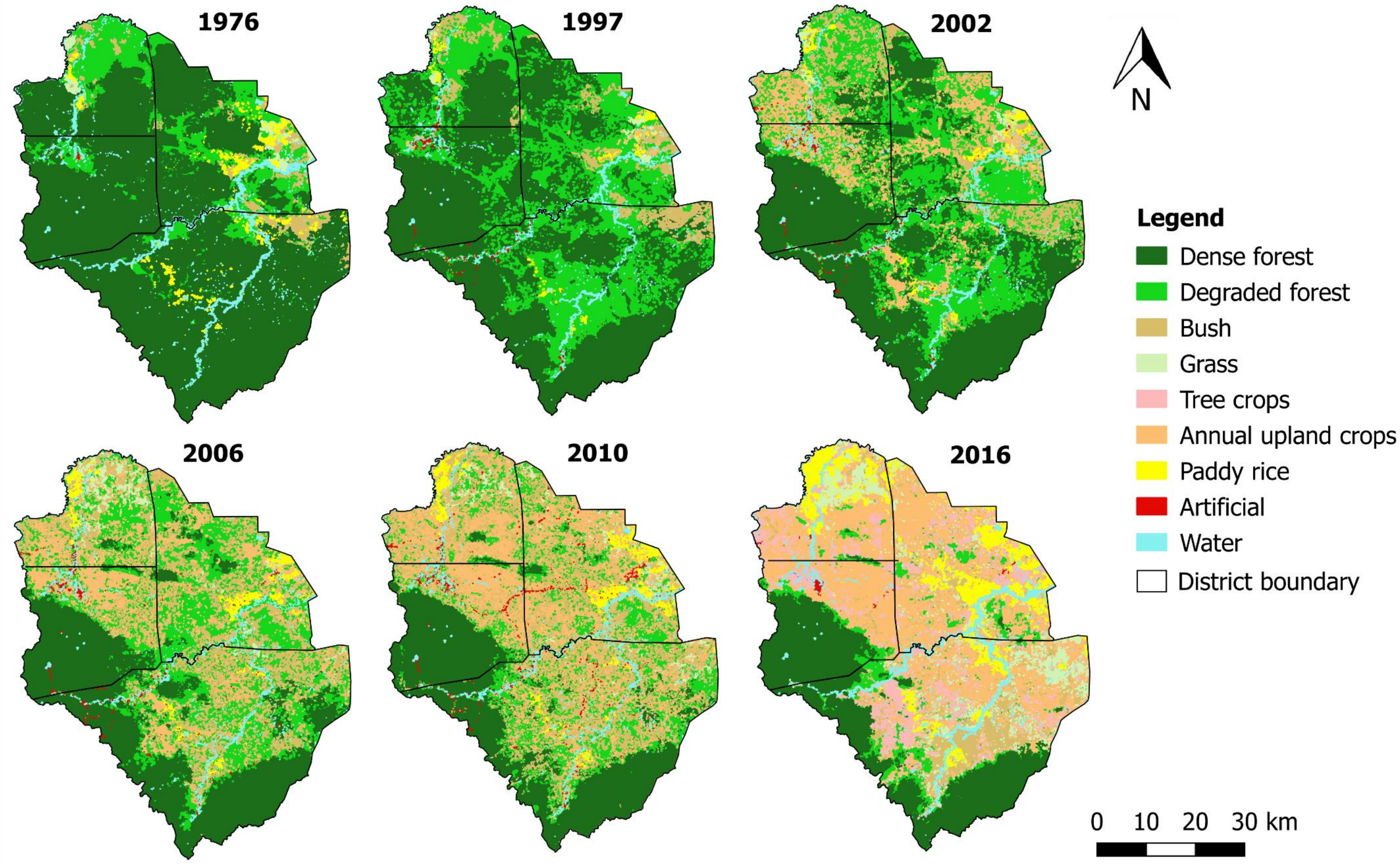


Figure 8: LUCC classification and changing patterns over the last four decades

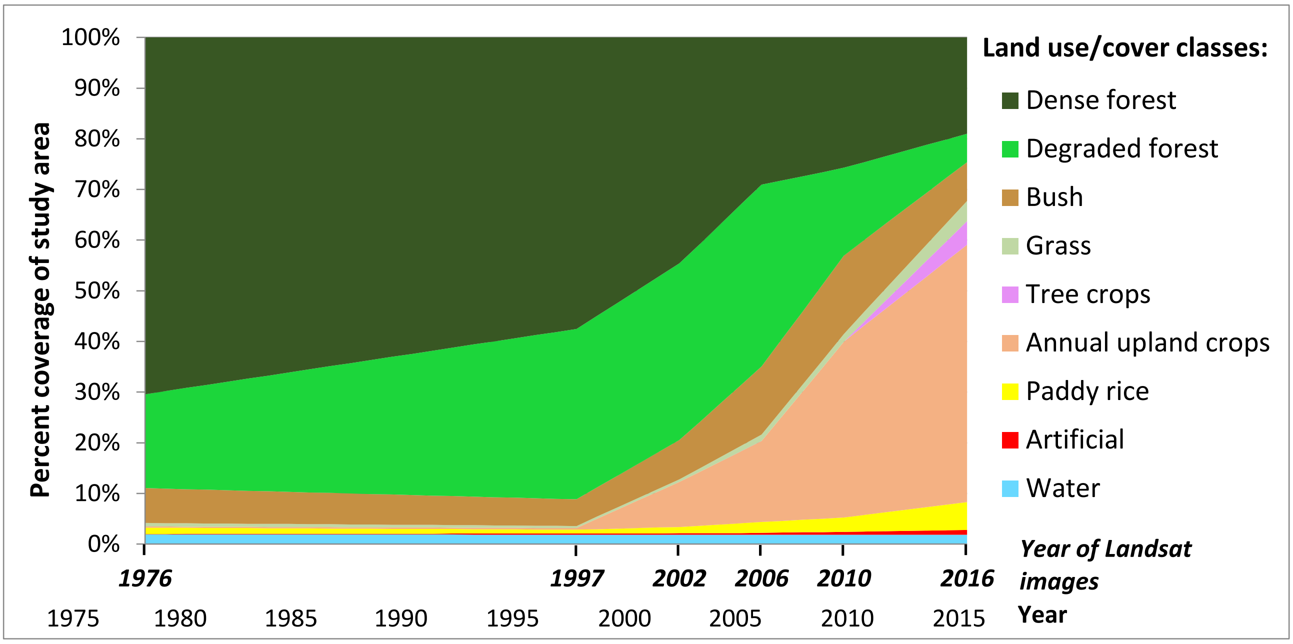


Figure 9: Evolution of LUCC in the study area based on time series of remote sensing data

2.3.2 Drivers of land use/cover change

The proximate causes and underlying factors that were identified and then through the successive steps described in the method section are presented in Figure 10. Each of them is described in the following sub-sections.

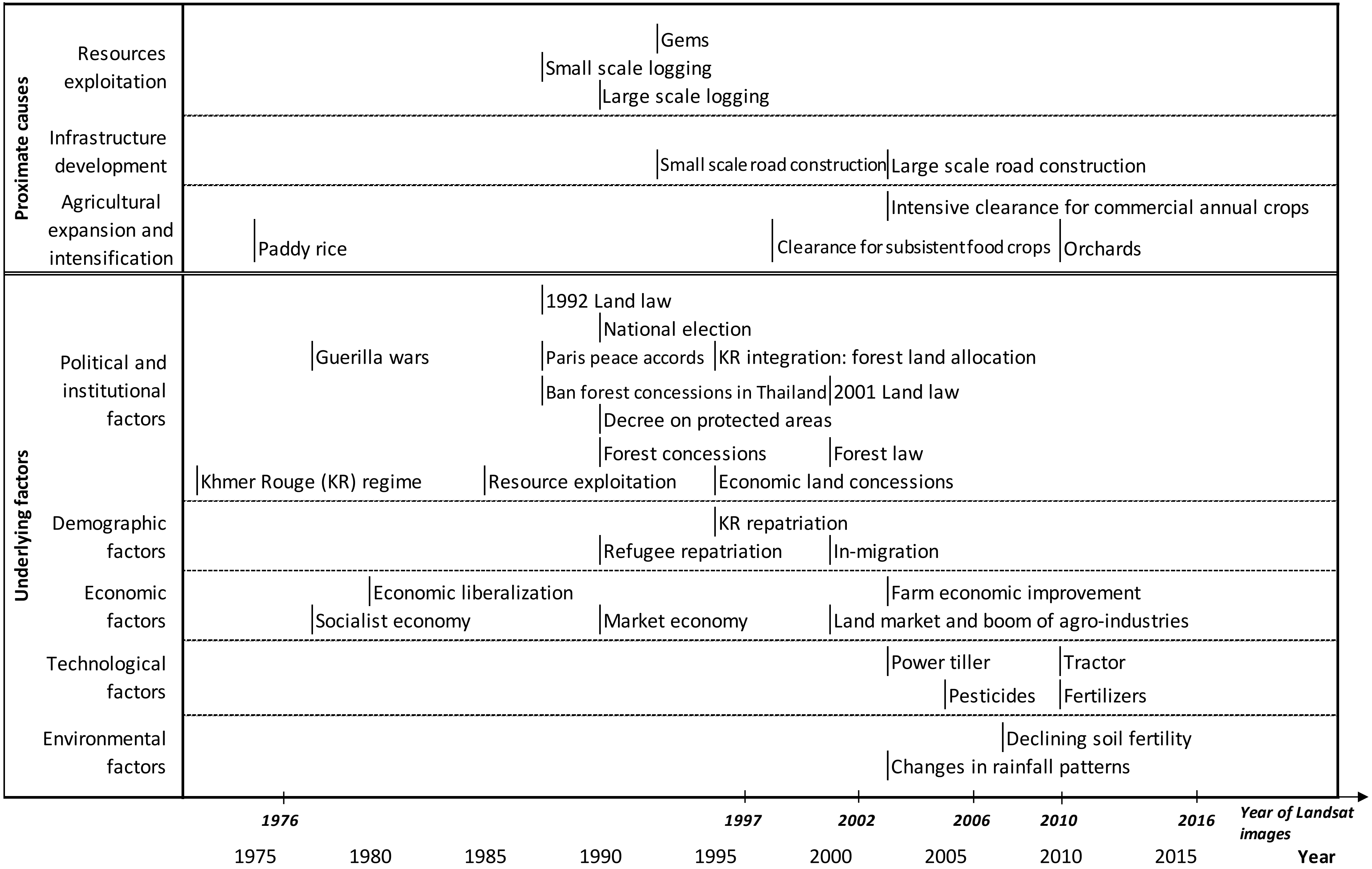


Figure 10: Historical milestones of proximate causes and underlying factors of LUCC

2.3.2.1 Proximate causes of LUCC

- Resource exploitation: the rush for timber and gems

Timber logging and gem exploitation started in the early 1980s along the borderlands and intensified from 1990 when a commercial agreement was reached between the KR, Thai companies and the Thai military (Le Billon, 1999). The Thai National Intelligence Agency reports that the KR generated approximately 106 million USD of income from timber exploitation between 1989 and 1992 (Stier, 1993). For the same period, the Thai Forestry Statistics reported timber imports equivalent to 687,809 cubic meters. By 1992, a total of 16 logging concessions were leased to Thai companies (Le Billon, 1999). Gem mining also witnessed a remarkable development in Pailin and Samlout. Mining started in 1989 with 6,000 miners and traders, expanding rapidly at an industrial scale with approximately 45 companies and 150 mined fields (Lechervy, 1996) and an average monthly income estimated at 5 million USD between 1990 and 1992 (Le Billon, 1999).

Although gem resources were rapidly exhausted, logging continued despite embargos on timber trading with the KR imposed by the government and the international community. The total quantity of logs exported by the KR from 1990 to 1998 amounted to 2.5 million cubic meters, which equaled the government's official exports during the same period. In fact, a large part of the logs exported by the government also originated from the KR controlled areas since the government agreed to recognize all the concession contracts signed with the Thai companies and the KR (Le Billon, 1999).

- Infrastructure development: paving the way to agricultural expansion

The dramatic expansion of agricultural areas occurred concurrently with the improvement and densification of the road network. While the war had left the rural infrastructure severely damaged and under total lack of maintenance (ADB, 2001), the Thai logging companies established in the North-Western region contributed to the considerable expansion of the road network for the purposes of timber extraction and exportation. Then, in 1996, the SEILA program together with a 'food for work' program carried out by the International Labor Organization and the World Food Program also mobilized funds from international aid to rehabilitate the rural infrastructure (Schulz and Huyssteen, 1999). Finally, in 2001-2005, an Asian Development Bank (ADB) loan financed the restoration and upgrading of all national and provincial roads throughout the Northwestern provinces (ADB, 2001).

Consistently, we compiled the four datasets and harmonized the information on road surface by differentiating three categories (asphalt, laterite and dirt road). Between 2001 and 2011, in the studied districts, the total length of (mainly laterite and dirt) roads increased sharply from 544km to 2,529km (Appendix 5). The increase was particularly important in Samlout and Rotonak Mondol Districts which benefited from large, pre-existing road networks before the war. Although 2014 data is not available for Pailin and Sala Krau, the road network expansion probably continued as in Samlout and Rotonak Mondol from 1,731km in 2011 to 2,719km in 2014. The decrease of laterite roads in 2011 could be explained by degradation due to intensive uses and floods, or possibly by inconsistencies between the different data sources.

- Agricultural expansion and intensification: shift to upland boom crops

According to Department of Agriculture statistics, the cultivated area in rainy seasons of annual and perennial upland crops (excluding paddy areas) in all study districts increased exponentially from a few thousand hectares to 145,000 hectares[1] over the past 15 years (Figure 11). Soybean and peanut were the dominant crops before 2004, although they were replaced afterwards by hybrid maize. The area of maize increased sharply at 72 percent per year between 2001 and 2009, while cassava expanded rapidly from 2014, mainly at the expense of maize, to cover 80 percent of the total agricultural land in 2016. The area under industrial trees expanded between 2006 and 2009 at around 130 percent per year, mainly through the development of rubber plantations. Subsequent expansion then occurred with the development of pepper plantations. Orchards – made up of about 80 percent of mango and longan plantations – witnessed rapid expansion periods between 2005 and 2006 (mainly with longan in Pailin) and again between 2015 and 2016 (mainly with mango in Rotonak Mondol).

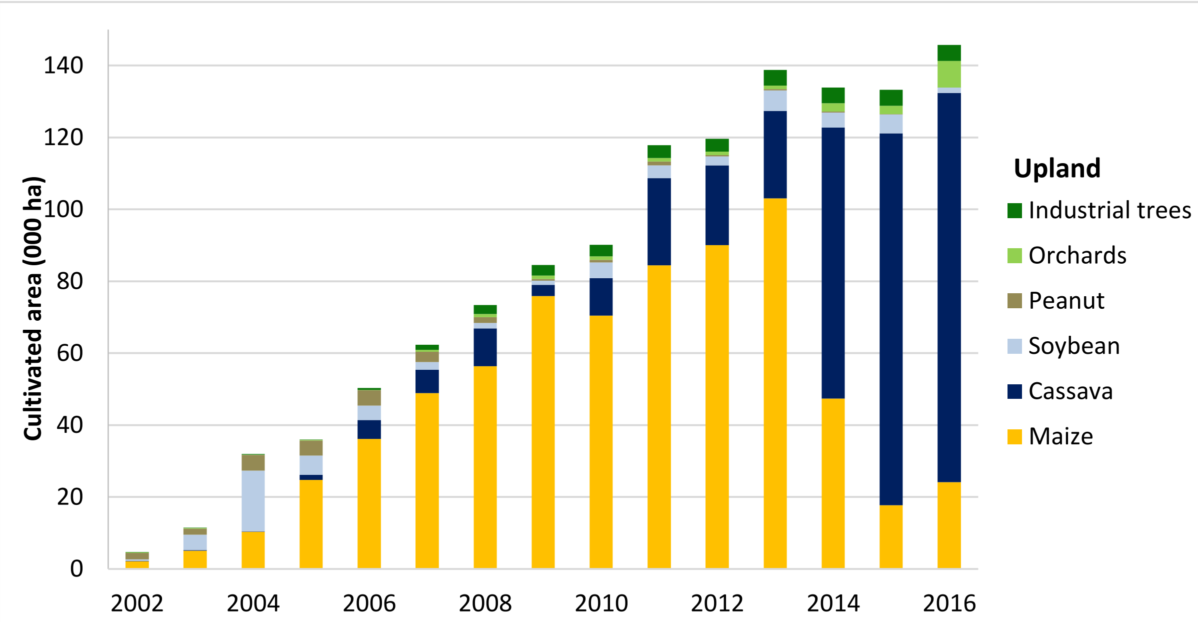


Figure 11: Changes in the cultivated area of the main upland crops in the study area

Source: Provincial Departments of Agriculture of Pailin and Battambang (2002-2016).

[1] Comparison of provincial statistics with the remote sensing data on annual and perennial crops shows a 23% difference in favor of remote sensing data. This could be explained by an underestimation by state actors of the extent of agricultural expansion in order to minimize forest conversion figures.

2.3.2.2 Underlying factors of land use changes

- Politics and institutions: the intricacies of Khmer Rouge re-integration

Cambodia was strongly influenced by the Cold War and, from 1969, underwent a devastating civil war for almost three decades (Le Billon and Springer, 2007). Following the downfall of the KR regime in 1979, the country witnessed far-reaching political and institutional changes: from a socialist state to a market economy with the abandonment of the autarchic policy of the KR in 1989, from civil war to peace in 1991, and from a single-party regime to a multi-party democracy in 1993 (Le Billon, 2000).

But in the Northwest of Cambodia, the conflicts between KR forces and the government army continued until 1998. In a context of withdrawal of all foreign political and financial support to Cambodia in the late 1980s and with logging activities being completely banned in Thailand in 1989 (Hirsch, 1995), the KR leadership decided to exploit the country's natural resources in order to finance its guerrilla war against the Cambodian government. The exploitation and trade of timber and gems was organized by the KR through concessions negotiated with Thai companies (Lebillon, 2000; French, 2002). But forest exploitation also benefited the government after the adoption of economic liberalization measures which allowed foreign companies to invest in forest exploitation (Hameiri, 2010; Hughes, 2003).

That period was one of intense political instability. It is associated with the KR's withdrawal from the Paris peace accords in 1991, the uncertainties regarding the political transition following the 1993 national election and competition between the two political parties constituting the national coalition, which were actually generating income from forest exploitation to build patronage networks across the country (Le Billon, 2002). In the absence of a consistent regulatory framework of timber extraction, the political turmoil had the effect of escalating timber extraction with each faction trying to generate as much income as possible. Overall, embargos on timber exportation from the KR controlled areas were never really effective (Le Billon, 1999).

In the mid-1990s, 23 protected areas covering about 3.3 million hectares (18 percent of national territory) including, in the study area, the Phnom Samkos Wildlife Sanctuary and Samlout Multiple Use Area (Royal Government of Cambodia, 1993). Starting from 1998, however, most of the unprotected forestland was allocated to demobilized the KR families and government soldiers following the so-called 'win-win' policy for the political settlement of the Cambodian conflict (Hun, 2006). Part of this reintegration policy aimed at providing the KR leaders with key positions within provincial and district administrations and lower-grade the KR representatives were given carte blanche to distribute land to demobilized soldiers. Given the considerable tracts of land suitable for cultivation, this reintegration marked the opening of the agricultural frontier and further created incentives for migration (Diepart & Dupuis, 2014).

- Demography: population increase fueled by in-migration flows

Population growth, land concentration and atomization, along with a ban on state land clearing promulgated in the 2001 Land Law led to a rapid decrease of household land holdings in the lowland areas of Cambodia (Diepart, 2015). With limited opportunities for off-farm employment, farmers in rural central rice-growing plains migrated to the peripheral uplands regions. As illustrated in Figure 12, this migration pattern had a significant impact on population growth in the four study districts. In 1997, a first migration peak coincided with the arrival of families repatriated from refugee camps located in Thailand. Subsequently, in-migration occurred with two important peaks in 2002 and 2007, consisting of migrants originating from neighboring districts and a flow of long distance migrants from the Southwest of the country where the demobilized KR soldiers are originally from (Diepart & Dupuis, 2014). In 2008 census data, the total population of the study area was 151,357 people of which 68 percent were migrants (NIS, 2009). Computation of the census data reveals that 72 percent of migrant household heads declared that their main reason for migration was the search for employment, while 72 percent of in-migrant population also considered farming as their primary occupation. Put together, these observations suggest that migration to the study area has been predominantly driven by farming households looking for agricultural land.

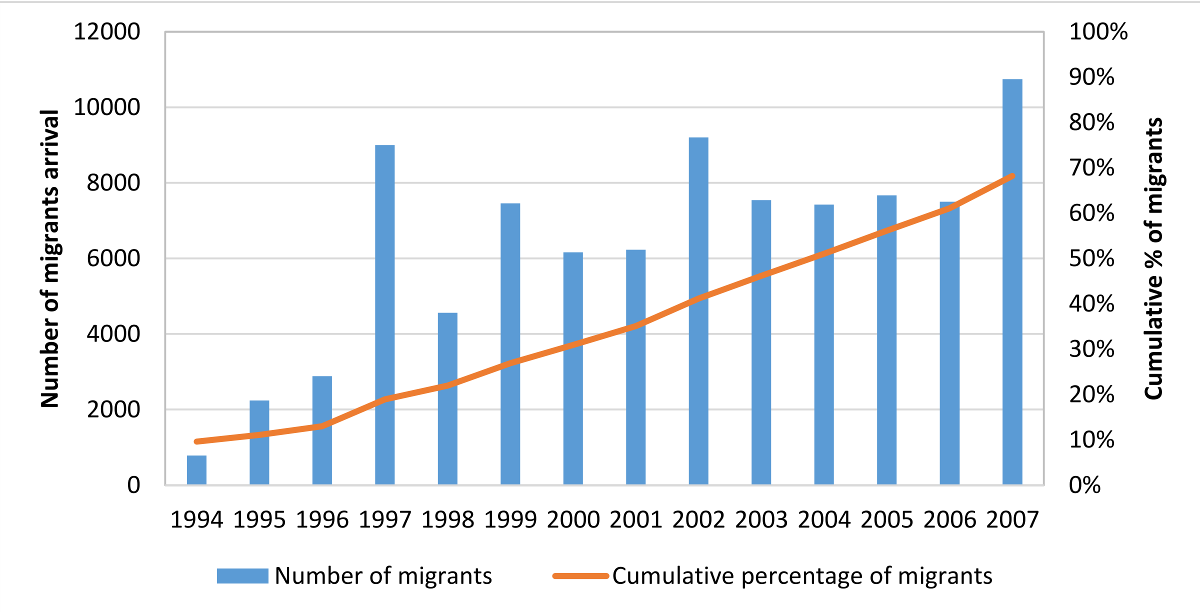


Figure 12: Percentage and arrival year of in-migrant population

Source: Census 2008

- Economy: liberalization policies, growth and indebtedness

Measures taken in the late 1980s – early 1990s to liberalize the national economy did not seem to have any noticeable influence on the economic growth of the Northwest until the KR integration in 1998 (ADB, 2001). Subsequently, the flourishing of regional agri-businesses started to have impacts on the demand and price of cereals. In the mid-2000s, hybrid maize was introduced by the Charoen Pokphand group and widely adopted by local farmers looking for higher profits (World Bank, 2015). Local farmers could thus quickly improve their living conditions. The housing and living conditions as well as assets of households in the study area improved considerably in the late 2000s. Based on commune databases 2006-2010 (NCDD, 2010) and 2011-2015 (PDP-BB, 2015; PDP-PL, 2015), the percentage of households with improved housing and transport equipment considerably increased between 2006 and 2015: zinc roof (+ 35 percent), latrine (+ 47 percent), access to drinking water (+ 27 percent) and ownership of motorbikes (+ 34 percent). We attribute the improvement of living conditions to increasing crop incomes, but also to increasing access to credit.

- Technology: intensification of upland farming practices

Based on the same commune database, the proportion of households to the number of tractors and power tillers increased by 2.4 and 8.4 percent respectively. Likewise, the percentage of households using pesticides and chemical fertilizers increased exponentially from 2006 to 2013 by 31 and 38 percent, respectively. The trend relative to pesticide use is confirmed by a 2011 survey conducted in Samlout and Sala Krau (Touch et al., 2016) as well as by key informant interviews and focus group discussions undertaken during the present study. In addition, information access to stimulation techniques for off-season fruit production encouraged the expansion of orchards since the harvest is scheduled for premium price seasons.

- Environment: decline of soil fertility and changes in rainfall patterns

Depletion of soil fertility under cropping practices with intensive tillage, mono-cropping, and little (or no) biomass input to the soil is generally reported as the main reason for a decline of annual crop productivity in the study area (Boulakia, Kong, & Eberle, 2013; Kong et al., 2016). Declines of 27, 20 and 16 percent of yield for maize, soybean, and cassava respectively were reported from 2008-2012, with more than 50 percent of farmers interviewed attributing the yield drops to soil fertility depletion (Touch et al., 2016). According to the in-depth interviews, in 2008 the maize's yield was on average 6-7t/ha in dry grain without any fertilizers on newly reclaimed land. But in 2016, the maize yield is only 4t/ha even with 50-100 USD/ha investment on chemical fertilizers.

The changes in rainfall patterns also contributed to yield decreases and led to adaptations of cropping practices by smallholder farmers. Historical rainfall data from 1920-

2012 recorded at the Battambang station show that the dry period increased from 1 to 3 months changing the rainfall distribution from a bi-modal (peak in May and September) to a mono-modal (peak in October) pattern (Doch et al.,, 2015). These findings confirm farmers' complains about delayed rainy season, more frequent drought and dry spells (Touch et al., 2017). Such a decline in annual crop yields has had significant negative impacts on the profitability of farming activities. As the price of annual upland crop such as maize and cassava is low, the resource-rich famers switched most of their annual crop to orchards. The majority of resource-poor farmers continue to cultivate the annual crops since they can't afford to invest in orchard; the installation costs are on average 500 USD/ha for mango and 2000 USD/ha for longan. In addition, the stimulation of off-season production costs 3000-5000 USD/ha.

Environmental changes induced by new cropping practices then became a driver of further land use changes, such as abandonment of initial boom crops and conversion to orchards, off-farm employment and migration to Thailand, land consolidation of some big farmers with the departure of smaller ones.

2.3.3 Interactions between proximate causes and underlying factors

We identified three key periods corresponding to relatively stable combinations of proximate causes and underlying factors of LUCC (Figure 13). The causes, factors, interactions, and their causal linkages are different in each period, and evolve from simple to more complex synergies over time.

During the first period, the main cause of LUCC was the resources exploitation (timber and gems) driven essentially by the political and institutional factors (civil wars and socio-political instabilities). The Thai companies who exploited timber and gem resources constructed a network of earth roads connecting to Thailand. In turn, the gradual expansion of the road network helped intensify the exploitation. The continuation of civil wars and the progressive withdrawal of foreign support pushed the KR to generate income from further exploitation of the abundant natural resources. The economic driver was thus largely influenced by political and institutional factors, and together accelerated the extraction of natural resources.

A major cause of LUCC during the second and third periods was agricultural expansion and intensification, which was reinforced by rapid infrastructure development. However, it was largely supported by demographic movements (in-migration) during the second period in addition to socioeconomic development. During the third period, technological changes, especially through the introduction of agrochemicals and mechanization and environmental degradations (erosion of soils and biodiversity triggered most of the changes in land use patterns. It appears that most of the changes in LUCC happened in the area were the influence of different factors combined as shown in the graphic representation in Figure 14.

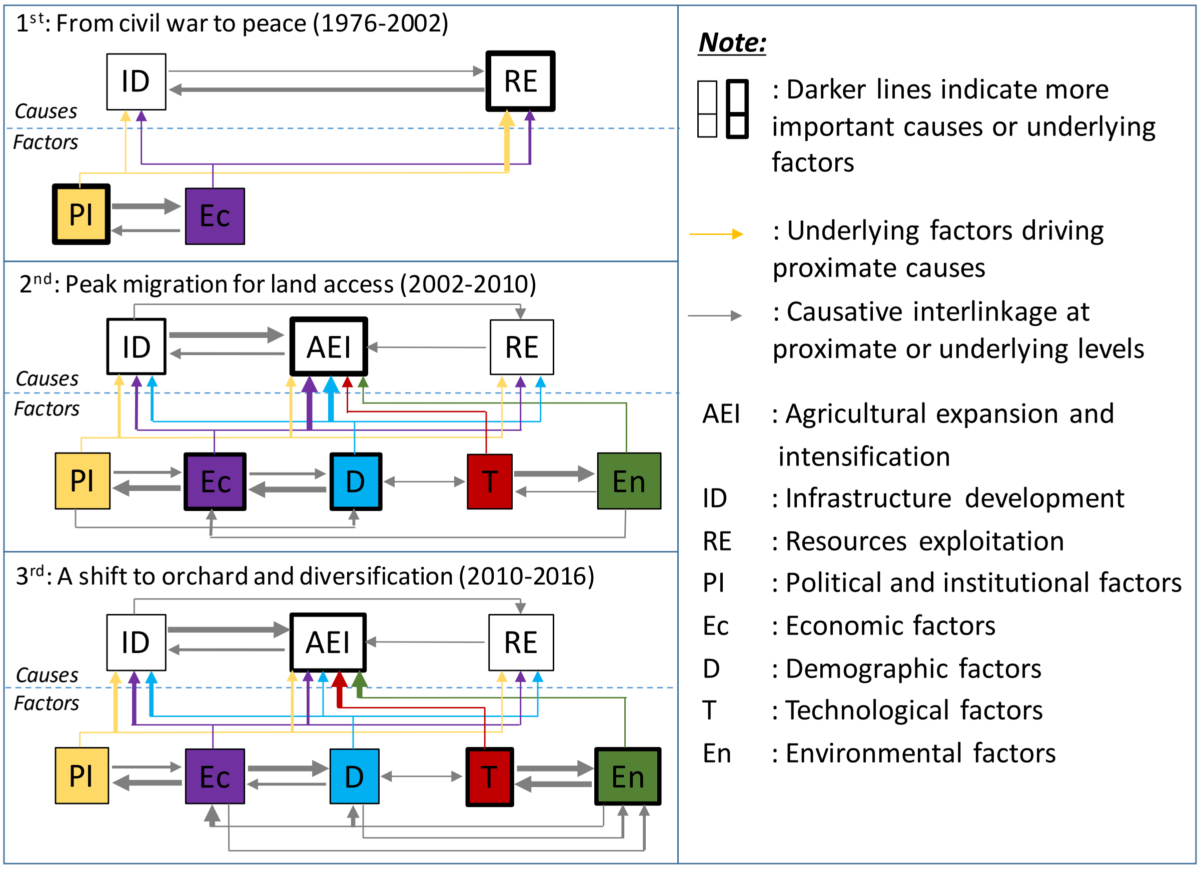


Figure 13: Relations between proximate causes and underlying factors of LUCC

NB: the size of the arrows is related to the strength - strong, medium, weak - of the interactions between factors as expressed by participants during the focus group discussions

We identified two turning points in the land use history of the study area corresponding to moments of complete reorganization of the land use systems (Figure 13). The first turning point was the end of the civil war. Socio-political instability and power competition, together with an embryonic legal framework and law enforcement were the underlying factors of LUCC. The impact on land use was tremendous as displayed in Figure 14a.

Peace making processes enabled the return of refugees from the camps in Thailand and significant movements of internal migration into the study area. Demobilized soldier families in the district were allocated forest land along the road (30m or 50m width by 1000m length). They gradually cleared the land to grow subsistence crops (paddy, sesame, mungbean, peanut, and upland rice) on small area ranging from 0.5 to 1.0 hectare per year per family depending on the household size. All land was appropriated by 2002, but not yet cleared. Some families sold or abandoned the land and moved to the town, while the others called to their relatives from the lowlands to move and settle in the Northwestern uplands. Nevertheless, the high risks of malaria and mines has somehow limited these in-migration flows

The second turning point is associated with the improved border market with Thailand for exporting agricultural produces and importing inputs. High profitability of annual upland crops, in particular hybrid maize, drove a massive expansion of agricultural land (Figure 14b). The expansion depended on the capacity of each household to clear the forest, i.e. family labor force and capital available to hire other migrants to work for them. Agricultural intensification, based on soil tillage, and use of chemicals inputs, rapidly affected the land productivity and the sustainability of intensive monocropping systems. Additional factors such as market fluctuations and rainfall uncertainties, pushed resource-rich famers to diversify their land use with orchards, livestock, and vegetables (Figure 14c).

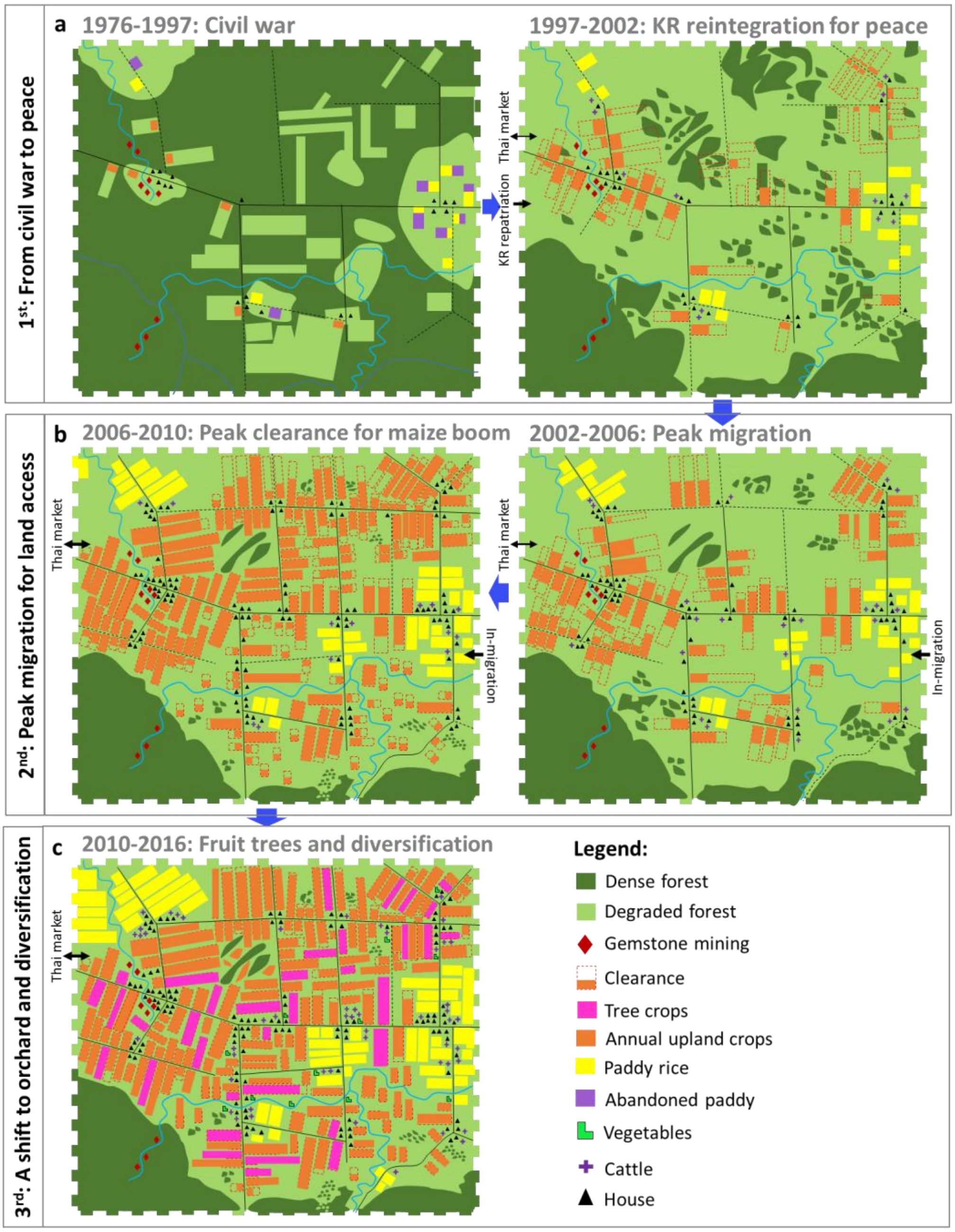


Figure 14: Graphic representation of the mechanisms of LUCC from 1976 to 2016

2.4 Discussion: understanding and influencing pathways of land use change

Our study intended to disentangle the complex processes of LUCC and the resulting land use patterns observed in Rotonak Mondol at successive dates over the past decades. This approach responded to a clearly stated need to develop a more refined understanding of drivers of change since indicators such as population growth, poverty, and road construction do not explain sufficiently LUCC in the Mekong Basin (Rowcroft, 2008). Interventions necessary for bending the curve towards more sustainable land use required additional insights into proximate causes and how they linked to underlying factors during the successive periods. Our comprehensive approach to LUCC combines qualitative data (literature review, interviews of resource persons and focus group discussions), and quantitative data (official statistical data, in-depth household surveys and remote sensing). It allowed to identifying the causes and factors then analyzing their interactions despite the fragmentation of available data (remote sensing and secondary data were not available for all dates or with the same geographic coverage) and inconsistencies across scales and periods. For example, different indicators used by different communes or change in time on data collection protocols did not allow for integration into statistical analyzes. While the proposed combination of methods (remote sensing and actor-based interpretations) allowed for LUCC interpretation at complementary spatial and temporal scales, it largely relies on the knowledge of the resource persons who were involved in the individual interviews and group discussions. The participant selection procedure and the facilitation skills of the researchers may therefore influence the results of the overall process. By combining individual and collective data collection processes, we managed the risk of biases due to power imbalance during group discussions. We also repeated the process in five communes of the study district and took care of including redundancy in the profiles of respondents to multiply the perspectives on the causes and factors addressed during the interviews and discussions (Appendix 6).

The rapid forest clearance was mainly driven by (i) the need to secure land tenure before more migrants would arrive and appropriate the land and (ii) the high profitability of hybrid maize during the "maize boom" (Castella et al., 2016). As land prices were increasing, the poorest households tempted to sell out the land and searched for other forest tracts to clear in increasingly more marginal lands as the expansion reached less favorable soils: stony, hilly, and/or remote. Boulakia et al. (2013) explained this process as a second push-pull factor in which high prices were the pushing factor while the remaining forestlands were the pulling factor. There was an active movement of land transactions over the whole study period, initially driven by incoming migrants and land expansion by smallholders, then more recently by land speculations and land appropriation by large-scale investors.

The patterns of LUCC associated with maize (2006-2011) and later cassava (2012-2014) that we described here in the Northwest of Cambodia are similar to the maize boom of the 1970s and the cassava boom of the 1980s that were observed in Northeast Thailand. They were also driven by highway roads construction, in-migration, the high profitability of newly introduced agricultural commodities, and available land resources observed (Riethmüller, 1988; Scholz, 1988; Sirisambhand, 1988). Likewise, a maize boom occurred in Northern Vietnam in the 1990s (Keil et al., 2008) and in the 2000s in Laos PDR (Slaats and Lestrelin, 2009). In all cases they were pulled by available forest frontiers, weak land governance and pushed by emerging economic opportunity and access to agro-chemical inputs. Then in all these former marginal landscapes, smallholder farmers continued for a while to shift from one boom crop to another.

After maize, cassava is the second boom crop due to its capacity to utilize the last remaining soil nutrients and to provide better profitability (Sopheapa, Patanothaib, & Ayec, 2012; Wenjun, Maofen, Aye, & Srey, 2016). Unfortunately, cassava lasted shorter than maize since its yield dropped significantly after a few year of monocropping (Boulakia et al., 2013). The cassava boom also happened over the same period in Northeast Cambodia as described by Mahanty and Milne (2016).

Farmers increasingly invested in the risky business of growing crops that are part of wider capitalist commodity production processes (Bernstein, 1977). High production costs due to increased agro-chemical inputs, continuous depletion of soil fertility, an uncertain market and climate trapped smallholders in the indebtedness. The household survey in Rotonak Mondol District found that 70 percent of interviewed households had loans with one or more Micro Finance Institutions, with 85 percent of total loans per household ranging between USD 1,000 and USD 1,500.

The same patterns of boom and bust were experienced in Thailand (Sirisambhand, 1988) and at the global level across the Amazon deforestation frontier (Rodrigues et al., 2009). The livelihoods of smallholders, that had improved gradually over the period of agricultural expansion and intensification (Touk, 2004), have deteriorated in relation with heavy land degradation and yield declines (Martin et al., 2013; Montgomery et al., 2017; Touch et al., 2017), that led to indebtedness, asset de-possession, and labor migration to Thailand (Diepart & Sem, 2018).

These changes marked the end of the agricultural expansion and intensification period. The agricultural frontier was reached long ago and there is no space left for agricultural expansion. The transformations based on mechanization and heavy use of chemical inputs has shown its limits. It is therefore essential to reinvent a new agricultural model. The agrarian system is reaching a new turning point referred to as diversification in Figure 13 and Figure 14. The causes and factors of future land use changes are recombining again and there may be room for research to influence these changes towards more sustainable pathways.

While turning their former maize fields into orchard plantations, many smallholders are still in the mindset of economic speculation on farming without visible investment in the sustainability of their production practices. They shift from one high-price crop to another with the same logic although orchards represent much higher initial investments and economic risks. Their capacity to seize the new economic opportunities depends very much on their patterns of capital accumulation over the previous period (Diepart & Dupuis, 2014; Mahanty & Milne, 2016). Wealthy farmers can afford to shift to orchards, while resource-poor farmers continue to bet on maize and cassava although some of them also diversify to livestock. The poorest households are left behind with no other option than selling their land and their labor force to the blossoming garment factories. During the recent land rush wave, some wealthy Cambodian from the cities (Battambang and Phnom Penh) and abroad (USA and Australia) as well as high ranking military officers bought large pieces of land and cleared them mechanically to install tree plantations, mainly orchards (Authors' survey, 2016).

Intervention methods need to adjust to the observed economic differentiation of farming systems. Each farm type has developed its own diversification logic and specific strategies to adapt to their changing environment. It is therefore crucial to understand the diversity of farms and their trajectories in time and space, and more importantly the farming decision-making process for land use changes and agricultural innovations under complex factors interacting in these rapid dynamics. Specific intervention mechanisms are required to break the cycle of boom-bust development and to enhance the resilience and sustainability of the system from the farm to the landscape level.

2.5 Conclusions

The analysis of remote sensing data showed that 61 percent (208,163 hectares) of forest cover was lost to upland crops over the last four decades in the study area. The remaining forest is located in protected areas. The LUCC in the Northwest of Cambodia is not a simple cause-effect relationship related to maize and cassava expansion, but rather a complex dynamic associated with different proximate causes and underlying factors interacting on different temporal and spatial scales.

Overall, three proximate causes and five underlying factors were identified. Their importance and their interactions are not the same along the three defined periods of changes. The agricultural expansion is the principal proximate cause of LUCC in the second period driven by market demand and high profitability of hybrid maize, vast available forestland with weak land governance and spontaneous in-migration of poor and landless farmers from populated lowlands. Agricultural transformations through technological innovations: machinery for land preparation and sowing, agro-chemical inputs also marked in the third period. Productivity decline of maize due to environmental degradation drove that third period of the agricultural diversification with a shift from cassava to orchards.

The boom crops engage smallholders in a risky business of growing crops that are part of a wider capitalist mode of production that alternately trap them into indebtedness and wage labor or outmigration to Thailand. It tends to broaden social differentiation with wealth accumulated among a minority of privileged farmers. The wealthiest can afford to shift to orchards with off-season production that is considered as the current boom crop, whereas the smallholders continue to bet on uncertain maize and cassava benefits due to weather irregularities and price fluctuations. Without appropriate interventions, farmers will most likely continue to jump from one boom crop to the next and thus face repeated negative consequences that deteriorate their farming economy and degrade the landscape as a whole. Understanding agricultural diversity and trajectories, as well as land use decisions will definitely help develop the appropriate interventions for resilient and sustainable farming systems.

Acknowledgements

We thank the farmers and the authorities in Rotonak Mondol district, Battambang province, who participated in this research. We are grateful to the officers of the provincial department of agriculture and planning in Battambang and Pailin province, who provided the agricultural and socio-economic data. We acknowledge the support of Ms. Audrey Jolivot at the Maison de la Télédétection in Montpellier, who supervised the first author for the analysis of remote sensing data, and of Ms. Malyne Neang at the ECOLAND research center of the Royal University of Agriculture, who facilitated the research implementation. The Agence Française de Développement (AFD) through the ACTAE project (Towards an Agro-ecological Transition in Southeast Asia) and Agropolis Foundation provided financial support to the research reported in this paper. We are very thankful to the journal editor and the two anonymous reviewers who made detailed and constructive comments.

Chapter 3

Characterizing the diversity of upland farming systems and their capacity to innovate in the Northwestern Uplands of Cambodia

Abstract

The Northwestern Uplands of Cambodia underwent a massive land conversion from forest to agriculture in the last 15 years. In Rotonak Mondol District, Battambang Province, we surveyed 365 randomly selected households, then conducted in-depth interviews with a sub-sample of 95 households to (i) characterize the diversity and trajectory of farming systems, (ii) assess farm performances and strategies and (iii) analyze the influences of farm structure on farmers' capacity to innovate. We used principal component analysis in combination with hierarchy cluster analysis to identify four main farm types: Upland crop-based smallholder farm (small farm) 25%, Upland crop-based large farm (large farm) 20%, Off-farm income dominated (off-farm) farm 35%, and Paddy based farm (paddy farm) 20%. The livelihood of paddy farms is centered on a rice-cattle combination with off-farm activities and annual upland crop farming for cash income. Large farms specialize in intensive and mechanized upland crops, including orchards. Small farms have a diverse activity portfolio including paddy, annual upland crops, and off-farm activities. The livelihood of the off-farm type is largely based on low-income off-farm activities. The time of arrival, initial cash and labor, relationship with local authorities, and/or social background are key factors defining farm structure and livelihoods. This, in turn, determined the farm's capacity to accumulate resources during the maize boom that occurred in this region between 2006 and 2011. In order to understand farm trajectories and their capacity to innovate it is essential to engage with farmers in co-designing sustainable alternatives to boom crops.

This chapter is based on the following research article:

Kong R., nd. Characterizing the diversity of upland farming systems and their capacity to innovate in the northwestern uplands of Cambodia. Submitted to *Agriculture, Ecosystems & Environment*

3.1 Introduction

Over the past 15 years, the Northwestern Uplands of Cambodia experienced dramatic changes in land use, involving a massive land conversion from forest to agriculture (Kong et al., 2019). In one of the last pioneer fronts in the region, farmers engaged in crop boom-bust cycles (Hall, 2011) with tremendous consequence on social differentiation, household economies (i.e. increased indebtedness), and land degradation. To break the boom-bust cycle described in Kong et al., (2019), it is important to understand the diversity of farming practices and how it built up in time through individual farm trajectories.

Farming system research considers the farm as a system and analyzes interactions between its internal components (i.e. sub-systems) and external biophysical and socioeconomic factors (Shaner, 1982). We define a farming system as a population of individual farm households that transform, under the influence of external factors and internal resources (land, labor, and capital), crop and livestock systems to useful products for sale and/or for household consumption (Dixon et al., 2001; Fresco and Westphal, 1988). Acknowledging the reality of farming system diversity is the first step in improving their performances (Ruben and Pender, 2004). The diversity can be better understood by grouping farming systems sharing similar characteristics in terms of farm resources, crop patterns, livestock, on/off farm activities, strategies and constraints (Köbrich et al., 2003).

Landais, (1998) used the term "typology" to explain farm grouping as the science of type characterization. Alvarez et al. (2014) summarize four purposes of developing farm typologies: (i) identifying appropriate interventions for each farm type, (ii) understanding how the interventions could be disseminated at a larger scale, (iii) selecting representative/prototype farms for detailed analysis, and (iv) extrapolating ex-ante impact assessments to a larger scale. Typology methods can be grouped into two categories: structural, i.e. describing farm resources and asset levels, and functional, i.e. describing farm strategies and dynamics typologies (Tittonell, 2014). The method selection depends on typology objectives and resources, but Alvarez et al. (2014) recommend combining structural typology with multivariate statistics known as 'dimension reduction' or 'data-reduction' techniques (Pacini et al., 2013), complemented by expert knowledge. The benefits of combining these two methods are demonstrated for example in the study of Berre et al. (2016) in Southern Ethiopia and Kuivanen et al. (2016b) in Northern Ghana.

In Cambodia, a household typology has been developed at the national level based on the level of income calculated from the annual national socioeconomic survey (Sann, 2010; Tong, Lun, Sry, & Pon, 2013). The typology initially included five types: poorest, next poorest, middle, next richest, and richest, but was simplified to only three types: poor, medium and rich. It frequently relies on expert knowledge and is generally used in agricultural and rural development activities of government and non-government organizations. However, this classification system does not provide information on how the households reached their status as the typology is static, nor the leverage points to lift the least endowed farms out of poverty.

Nguyen et al. (2015) and Jiao et al. (2017) used multivariate statistics to construct a farm typology based on natural resource dependence in the North and the changes of livelihood strategies in the center of Cambodia respectively. Recent academic research in the Northwest built a farm typology using a participatory approach based on farm history, resource base, and production systems to understand access to land and government services (Diepart and Sem, 2018). While these recent typologies dealt with the time dimension in understanding how household diversity built up in time, the entry points for interventions could not be explicitly addressed because the performance and sustainability of each farm type were not studied.

Under the massive and rapid LUCC that prevail in a pioneer front context, farmers are often believed to do the same things, i.e. 'grow maize', in the case of the Northwestern Uplands of Cambodia in the 2000s. The diversity of farms and their trajectories is little known (Bertrand, 2011). However, the multiple reasons why farmers 'grow maize', their decision-making process, their performances and capacity to innovate are important underlying factors of the crop booms (Ornetsmüller et al., 2018). These individual drivers of change need to be understood in order to target interventions to the specificities of each farm type and design relevant intervention mechanisms. In this paper, we conducted household surveys in ten villages to characterize the diversity of the farming systems and how they are organized in time and space. In addition, we assessed the technical and economic performances of each farm type. Finally, we investigated the influence of farm structures on their capacity to innovate. This approach is aimed at providing leverage points for interventions adapted to the diversity of farming systems, the rapid pace of land use change in a pioneer front context, and the capacity of each farm type to innovate.

3.2 Methodology

3.2.1 Study area

Rotonak Mondol District in Battambang Province is one of the four districts where massive land use, land cover changes and rapid transitions of farming systems have been reported by Rada Kong et al., (2019). The district was also selected by the Ministry of Agriculture, Forestry and Fisheries (MAFF) to implement a pilot extension program on Conservation Agriculture (CA) in the Northwestern Uplands of Cambodia (R. Kong et al., 2016). It is geographically located between 12°43'26.55"N and 13°5'1.42"N latitude and between 102°45'7.42"E and 103° 2'57.80"E longitude with an elevation of between 30m and 435m above sea level. The district area is 792 km^2 with a density of 60 people per km^2. It is a dominantly undulating upland area with small lowland paddy areas (Figure 15). Based on Crocker (1962), there are four soil types in the district, including 39% *Brown hydromorphics*, 34% *Basic Lithosols*, 5% *Latosols*, and 22% *Regurs*, that are generally considered as medium to good soils.

The region follows the South-East Asia Monsoon of 5-month dry season from December to April and 7-month wet season from May to November. The data from the provincial weather station in Battambang from 1982 to 2016 shows an average annual rainfall of 1,310 mm, steadily increasing from 45mm in March to as high as 256mm in October. The average temperature is 28ºC with an average maximum of 36ºC in April and an average minimum of 20ºC in December. The average relative humidity is 80% with a maximum of 86% in September-October and a minimum of 72% in March (Martin et al., 2013). Topography, soil types, and rainfall patterns allow farmers to practice two crop cycles per year, i.e. a dry season cycle from February-March to May-June and a wet season cycle from July-August to November-December, except for cassava, which is a more than 10- month cycle crop.

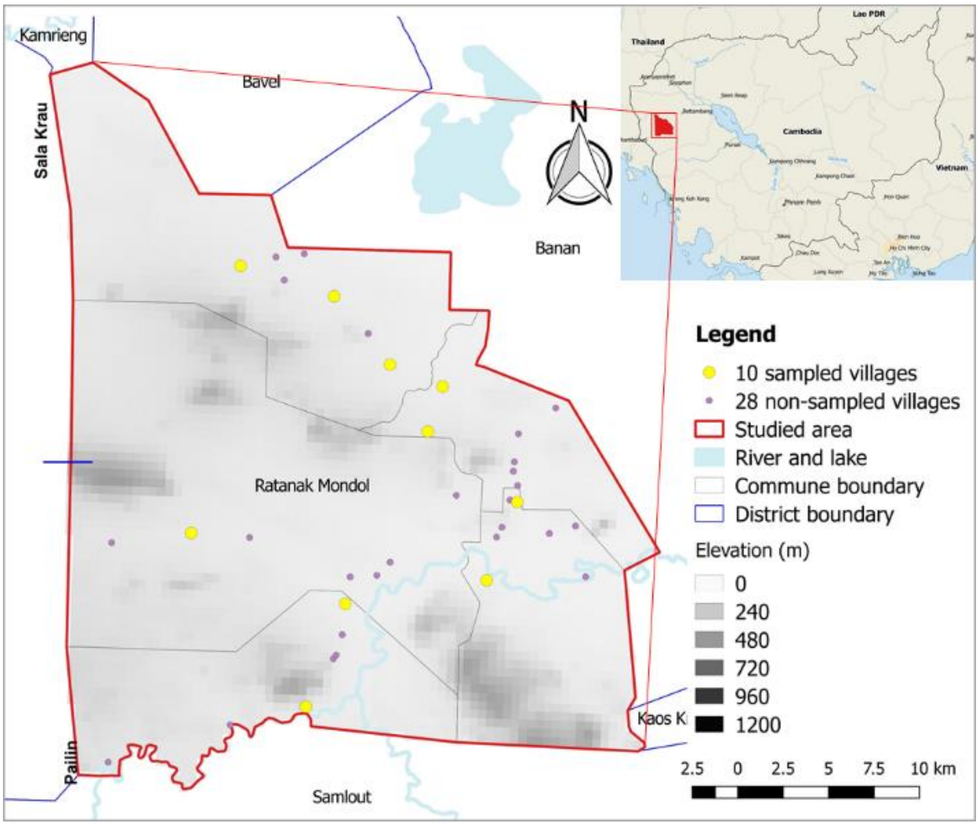


Figure 15: Location of study area

3.2.2 Data collection

Ten villages out of 38 in Rotonak Mondol District were stratified and randomly selected, distributed over the five communes. The village stratification was done through two multivariate statistical techniques sequentially, the Principal Component Analysis (PCA) and Agglomerative Hierarchical Clustering (AHC) analysis. The random selection was proportionally done. The households were randomly selected from the ten sampled villages based on the survey system online calculation with a 99% confidence level and a 19%

confidence interval (https://www.surveysystem.com/sscalc.htm). The list of villagers used in each sampled village to randomly select the households was obtained from the village chief or communal police office. In total, 365 households were selected for the household questionnaire survey. To select households for in-depth interviews, we stratified these sampled households based on identified farm type and randomly selected 95 households. The details of household sampling procedures are provided in Table 3.

Table 3: Number of sampled households and villages

Sampled village	Commune	Total households in 2016	Samples for questionnaire		Outliers	Sampled for in-depth interview	
			No.	%		No.	%
Baribour	Sdau	161	36	22	0	10	28
Kouk Choar		97	31	32	0	8	26
Chi Pang	Phlov Meas	137	35	26	0	9	26
Phlov Meas		291	40	14	2	10	25
Ou Khmum	Reaksmei Songha	330	41	12	0	11	27
Pich Changva		174	37	21	1	10	27
Reaksmei Sangha		453	42	9	4	10	24
Serei Voant	Andaeuk Haeb	146	35	24	0	9	26
Thvak		97	31	32	0	8	26
Svay Sar	Traeng	175	37	21	0	10	27
Total		2,061	365	18	7	95	26

The household survey was conducted to collect information related to household composition and education, labor resources, land holdings, household assets, agricultural assets, natural resources, production systems, production costs, gross incomes and off-farm activities. In addition, the questionnaire included a list of questions regarding technical and organizational innovations. The innovations are defined as any practices that farmers adopt and adapt to improve their resilience to land productivity decline, increased production costs, decreased input use efficiency and increased vulnerability to market and climate uncertainties.

Eight innovations are defined and listed in the questionnaire (Appendix 10) with options for additional innovations in case farmers request to include them in the questionnaire. During the interviews, the enumerators discussed with the farmers the successive farming practices they used since their arrival time in the area. The farmers were asked further about the reasons for adoption, number of years of experience, or the reasons for stopping or continuing with these practices. In-depth interviews were conducted to investigate the history of migration and settlement, conditions of land access, changes in farm resources including labor, land, assets, evolutions of land use and farming practices, farm constraints, decision making processes and strategies.

To perform the PCA and AHC analysis for the village typology, the 2016 communal database was explored for a number of variables related to the uses of agricultural inputs and machineries, demography and socioeconomics. In addition, data on village agricultural land use in 2016 was obtained from the LUCC classification based on Landsat imagery (Kong et al., 2019). A previous agrarian diagnosis and farm typology conducted in two of the 10 selected villages in 2010 was reviewed to assess the changes in the diversity of farming systems in time (Bertrand, 2011).

3.2.3 Data analysis

We analyzed data according to the three objectives of the study as indicated in Table 4.

Table 4: Analytical framework

Objectives	Scales	Methods	Analysis	Outputs
1. Characterizing farming systems diversity and trajectories	District Village Farm	- Extraction of communal database - Village LUCC in 2016 (Kong et al., 2019) - Review farm typology in 2010 (Bertrand, 2011) - 365 household questionnaire surveys in 2016 - 95 in-depth interviews in 2017	- Multivariate analysis of village and farm diversity - Comparison of the 2010 and 2016 typologies - Retrospective analysis and categorization of farming system evolution in time	- Village typology - Farm typology - Graphic representation of farming system trajectories and drivers of change
2. Assessing the performances of farming systems	Farm Field	- 95 in-depth interviews in 2017	- Technical and economic performances of cropping systems - Farm's income and activity portfolio	- Cropping system performances by type of farming system and its impacts on farm's income
3. Investigating the influence of farm's structure on its capacity to innovate	Farm Field	- Review 2010 farm typology (Bertrand, 2011) - 365 household questionnaire surveys in 2016 - 95 in-depth interviews in 2017	- Categorization of innovative systems by type of farming system - Identification of factors influencing innovation	Explanation of the influences of farming system structure on the adoption of innovative practices

3.2.4 Characterizing farming systems diversity and trajectories

3.2.4.1 Village typology

Fifteen variables were used to run the village PCA (Table 5). The first five factors showed eigenvalues higher than one and explained 72% of the variability between the villages. The first two factors were then selected to run the AHC as they combined several variables; the first factor combined crop area, paddy area, use of planter, number of cattle, tractors and insecticide sprays, while the second factor consisted of built-up areas, cars owned, working females, trade and shops, and total households. The AHC analysis resulted in four village clusters or types with 72% variance decomposition between clusters (Appendix 7). These are Urban Village (5%), Upland–Intensive Village (8%), Lowland-Diversified Village (47%) and Upland-Diversified Village (40%).

Urban village type is characterized by a high population, large built-up areas and high availability of services. This type was excluded from further village selection as the research focused on farming systems, which concerns only a minority of households in urban villages. The lowland-diversified village type has larger paddy areas, up to 37%, and a high proportion of households owning cattle, up to 50%. Farming is diversified with upland crops, paddy and cattle, and is characterized by low intensification in terms of use of agro-chemical inputs and machinery (tractors, planters, etc.). On the other hand, the upland-intensive village is characterized by the largest share (97%) of upland area and the highest percentage of households using agrochemical inputs and machinery. The average farm size is bigger than for other village types. The upland-diversified village type has similar characteristics as the upland-intensified village type in terms of agrochemical input use and machinery, but to a lesser extent. In addition, it also has larger paddy areas and more cattle raising households (Appendix 8).

Table 5 : Descriptive statistics of the variables used in PCA for village clusters (N = 38)

Name of variables	Code	Description	Unit	$\overline{x}$	σ
Demography					
Total household	TH	Total household number	hh	255.8	133.6
Economy					
%Female in services	FS	% female number of total females, from 18-64 years old working mainly in services	%	7.6	9.6
%Shop	SP	% shops/stores per household selling goods and services except those in the market	%	2.0	2.9
Household asset					
%Family car	FC	% of households owning family car	%	1.6	1.6
%Cattle	C	% of households raising cattle	%	31.3	26.8
%TV	TV	% of households having zinc-roof house and television	%	53.8	26.1
%Tractor	T	% of households owning a tractor	%	2.1	2.1
%Power tiller	PT	% of households owning a power tiller	%	7.5	5.1
%Planter	P	% of maize-planters per household	%	0.5	1.2
Agricultural input					
%Insecticides	IC	% of households using insecticides during last year's cropping season	%	64.0	29.0
Land use					
%Built-up area	BA	% built-up area of total village land	%	1.7	4.7
%Crop area	CA	% upland annual and perennial crop area of total village land	%	59.7	22.7
%Paddy area	PD	% paddy area of total village land	%	16.6	18.9
%Plantation area	PA	% of wet area of total village land	%	8.7	13.7
%Paddy<1ha	PD1	% of wet area of total village land	%	16.7	18.6

Note: $\overline{x}$ = Mean; σ = Standard deviation; hh = Household

3.2.4.2 Farm typology

Variables were selected from the questionnaire survey to characterize the structures and functions of the farming systems, and their performances (Table 6). We included the variables related to the land size and the composition of land uses that were used as a basis for the functional typology in 2010 (Bertrand, 2011), resulting in the selection of 14 out of 27 variables to perform the PCA. In addition, boxplots were used to identify outliers, for example 7 households were taken out and kept for supplementary observation. The 7 households are capitalist farms with high income and assets, which are considered outliers and representing about 2% of the sample population.

The first two factors used for the AHC analysis capture 44% of the variability. The main variables that explain the first factor include total land, income from crops, production cost, off-farm income, power tiller, and total assets. The second factor combines paddy area, rice deficiency, cattle, and annual upland crops. The AHC resulted in four major farm clusters with 64% variance decomposition between clusters (Figure 16).

Table 6: Descriptive statistics of the variables used in PCA for farm clustering (N = 365)

Name of variables	Code	Description	Unit	$\bar{x}$	σ	PCA
Farm labor						
Family member		Total family members	person	4.9	1.7	
Working labor		Total family members working more than 25% either on farm or non-farm	person	3.3	1.5	
Farm labor	FL	Total family members working on farm only	person	2.3	1.3	yes
% migration	M	% of family members living outside of the village more than 25% of their time	%	11.9	22.3	yes
Education of household head		Number of years education	year	4.2	3.4	
Age of household head		Age of household head	year	46.8	13.3	
Farm land						
Total land	TL	Total land area both cultivated and fallow including rent-in and rent-out	ha	4.3	4.9	yes
Cultivated land		Total cultivated land area computed based on area per crop and per cycle	ha	4.5	5.4	
Land/Labor ratio		Cultivated land area per farm labor unit		2.0	2.8	
%Paddy area	P	Share of paddy area to total farm land	%	25.5	32.6	yes
%Annual crop area	AC	Share of annual upland crop area to total farm land	%	50.1	39.5	yes
%Orchard		Share of orchard area to total farm land	%	6.6	18.6	
Farm's finance						
Total asset	TA	Total value of all assets calculated as the sum of real purchased price	$	2,888	4,293	yes

Production costs	PC	Total cost of hired service and labor for all crops	$/year	744	1,117	yes
Debt	D	Total pending debt both formal and informal credits	$	1,674	3,010	yes
Power tiller	PT	Number of power tillers owned per household		0	0	yes
Cattle	C	Total number of cattle of all ages	head	1	1	yes
Farm's income						
Total household's income	HI	Sum of income and profit from all household’s activities	$/year	4,681	4,348	yes
Crop's income		Sum of total production multiplied by sales price for all grown crops	$/year	2,510	3,435	
%Crop's income	CI	Share of crop's income to total household's income		52	36	yes
Low-income off-farm		Total wage or salary per year for unskilled works i.e. agricultural wage labor, construction work, house mate…etc.	$/year	1,177	2,605	
%Income of poor off-farm	PO	Share of low-income off-farm to total off-farm income		26	34	yes
High-income off-farm		Total profit or salary per year for skilled or services related work and provision i.e. agricultural services provision (plowing, sowing…etc.), collectors/traders, self-business...etc.	$/year	879	1,779	
Livestock income		Total income from selling animals per year	$/year	81	249	
Farm status						
House quality		The sum of score for roof, wall, latrine and well ranging from 2 to 8		4.4	1.1	
Rice deficiency	RD	Percentage of months without rice sufficiency in a year	%	61.0	43.3	yes
Year stay		Number of years the household live in the village.	year	16.46	8.95	

Note: $\bar{x}$ = Mean; σ = Standard deviation

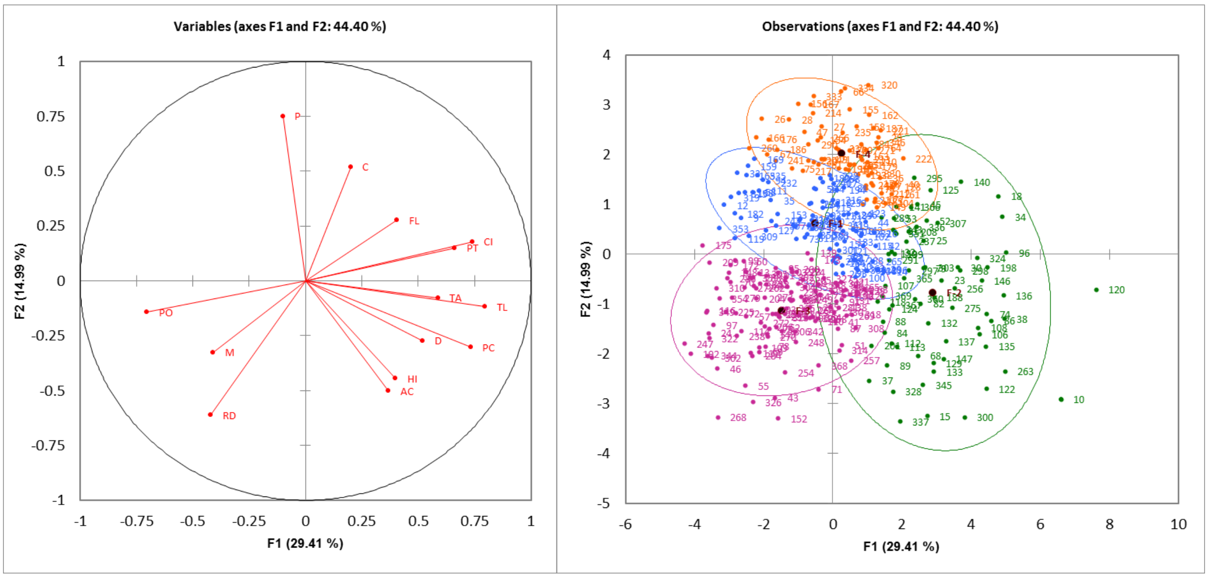


Figure 16: Graphic results of the PCA and distribution of farm types

The 365 surveyed households were then distributed into a matrix according to their farm and village types. The resulting representation of farm diversity revealed the influence of the village geographic characteristics on the relative proportion of farm types in each village. Historical information of the farm obtained through retrospective in-depth interviews was further consolidated by farm type and organized according to the three periods identified by Rada Kong et al., (2019). The three periods correspond to (i) from civil war to peace (1976-2002), (ii) peak migration for land access (2002-2010), and (iii) shift to orchard plantation and diversification (2010-2016). For each period, we characterized changes in farm structure using three indicators: land, labor, and capital.

3.2.4.3 Assessing the performances of farming systems and their capacity to innovate

The information from the in-depth interviews related to cropping systems, livestock systems, and other livelihood activities were consolidated by farm type. The technical and economic performances of a farming system were assessed based on the use of farm resources to manage cropping and livestock systems in a specific spatial and temporal combination. The evaluation method and terminology used is presented in Appendix 9, following Barral et al. (2011).

Off-farm activities, livestock systems and collections of natural resources, so called non-timber forest products (NTFP) are included in the calculation of household incomes. Off-farm activities are categorized into two types; high-income and low-income (Table 6). The income of low-income off-farm activities is calculated by summing up the monthly wage labor or salary for a period of one year. For the high-income activities, the farmers are asked to estimate the intermediate costs, salary of permanent workers, depreciation costs if any, and income per unit of service provision, for instance a plowing service per hectare. For natural resource collection, only few households (less than 10% of interviewed households) generate income through these activities; collecting mainly bamboo shoots, mushrooms, and fuel wood, the amount of which is highly variable depending on seasonal availability and accessibility. These generally contribute little to a farm's income.

The livestock systems comprise cattle that are raised by around 40% of interviewed households, in particular in the villages with large areas of paddy. The production system is similar to the traditional rice and cattle production in the lowland regions (Nesbitt, 1997), which is highly extensive without external inputs. The cattle ranching system enhances paddy productivity through the provision of feedstock with rice straw and manure to fertilize the paddy fields, and it is a form of capital accumulation and a financial safety net. Therefore, the income calculation takes the average annual income over the last three years assuming that intermediate costs and depreciation costs are negligible.

The analysis of cropping system performances includes the description of techniques used, intermediary costs, land productivity and labor productivity. Based on the information collected during the in-depth interviews, we categorized the crop successions or associations into 7 main cropping systems: cassava, maize, maize after secondary crops (mungbean, sesame, or peanut), paddy, vegetables, longan and mango. The vegetable-based cropping systems combine leafy green (lettuce, spinach, etc.), cruciferous (cabbage, cauliflower, etc.), and marrow (cucumber, eggplant, etc.).

The last step consisted of analyzing the influence of a farm's structure on its capacity to innovate. We investigated the relations between the farm types and the innovations reported by farmers through in-depth interviews. The innovations listed in the questionnaire (**Appendix 10**) were grouped into 10 innovations, 3 of which are organizational innovations. Farmers' cooperatives and community forestry are official organizations registered by the MAFF, while other farmer organizations are informal, created mostly by the development operators as part of their capacity building process and collective learning toward an official organization such as a farmers' cooperative.

3.3 Results

3.3.1 Farm typology

The 4 main farm types identified are: Upland crop-based smallholder farm (Type 1) 25%, Upland crop-based large farm (Type 2) 20%, Off-farm income dominated farm (Type 3) 34%, and Paddy based farm (Type 4) 19% (Table 7). The 7 outliers could be subdivided into two types: off-farm based investor (outlier 1) 0.5% and farm based investor (outlier 2) 1.5%. The outlier 1 type is characterized by high income from off-farm activities, which includes commercialization of agricultural and non-agricultural products, land brokerage, etc. Their farm size is among the largest in our sample (17ha) and is mostly used for orchards (76% of total farm area). In contrast, the outlier 2 type concentrates on farming activities on their large farm using their land for both orchards and annual upland crops. They own their machineries (i.e. tractor) and have a high financial throughput (25,900$ annual debt). They practice the most intensive and mechanized cropping systems in the district. In addition, they use their machineries to provide agricultural services to other farmers, providing additional off-farm income.

3.3.2 Farm characteristics

Upland crop-based smallholder farm. Type 1 (small farm) is characterized by relatively balanced farm land use between paddy (35%) and upland crops (40%), and balanced farm income with 53% and 45% generated from crop cultivation and off-farm activities respectively. Off-farm income mainly relies on low-income off-farm activities, which accounts for 29% of total income. With low to medium capital (total assets), land area and farm labor, this farm type generates relatively low household income in spite of having diversified income sources. They tend to diversify farm activities as well as the income sources as their level of rice deficiency is up to 58%. They manage to earn additional income from off-farm activities through migration. Annual crop and orchard production involves high production costs (126$/ha) and annual debt (881$).

Upland crop-based large farm. Type 2 (large farm) is characterized by a high level of total assets (7,500$) and larger farm size (~11ha). The high level of agricultural investment (202$/ha production cost) reveals farmers' strategies of farm intensification and mechanization. For that, they mobilize high farm labor (2.8) to cultivate annual upland crops (70% of the total area) and orchards (11% of the farm area), which contribute 79% of the total farm income (~ 9,000$). To operate such a large-scale production (for the local context), this farm type needs to take economic risks by contracting annual loans of up to 4,800$. This high level of debt and large cultivated area is made possible by a higher level of capital and assets (machineries, etc.) involved in farming activities. They also tend to diversify their activities as their paddy area covers only 56% of their needs (rice deficiency 44%). Off-farm activities, in particular high-income off-farm activities, provide additional income.

Off-farm income dominated farm. Type 3 (off farm) is characterized by small farm size, low total assets, and a high percentage of migration. Their livelihoods are largely dependent on off-farm activities, up to 68% of total household income. Low-income activities (44% of total farm's income) make up the largest part of off-farm activities, and mostly rely on migration work. Because of their low risk management capacity, they use 60% of the small farm area for annual upland crops. However, production is relatively intensive with 323$/ha production cost. Having the highest rice deficiency (97%) and the smallest farm size (1.8ha) (Table 6), this farm type tends to prioritize a diversity of off-farm activities, leaving farming activities as secondary income sources.

Paddy-based farm. Type 4 (paddy farm) owns larger areas of paddy land than other farm types. They have the highest number of cattle and the lowest rate of rice deficiency. They own on average 3.8ha of land, of which 60% is used for paddy production and about 25% for annual upland crop. Even though this farm type has higher total assets (2,400$) and debt (960$) than Type 1, they invest less in crop production with only 90$/ha production costs. As they have larger cattle herds and a larger paddy area with almost no rice deficiency, they are often more conservative than other farm types and do not take risks in farming intensification. Their objective is to generate cash income from non-rice crops and off-farm activities with as low production costs and as few risks as possible. The off-farm activities largely take place in the vicinity of the farm (only 4% migration) contributing 36% to the total farm income as a complement to crop income (64% of total income).

Table 7: Characteristics of farm types and P-value

Farm cluster	Type-1	Type-2	Type-3	Type-4	Outlier 1	Outlier 2	Total	P-value
Cluster name	Small holder	Large farm	Off farm	Paddy farm	Off-farm investor	Farm investor		
Number	90 (25%)	73 (20%)	125 (34%)	70 (19%)	2 (0.5%)	5 (1.5%)	365	
Farm labor								
Family member	4.9	5.1	5.0	4.7	3.0	4.6	4.9	.610
Working labor	3.3	3.6	3.2	3.3	3.0	3.4	3.3	.365
Farm labor	2.5	2.8	1.8	2.8	2.0	2.4	2.3	.000
% migration	8.8	6.3	21.8	4.0	50.0	27.0	11.9	.000
Education of household head	4	5	4	5	6	8	4	.066
Age of household head	45	48	46	49	47	45	47	.130
Farm land								
Total land	3.0	10.7	1.8	3.8	17.2	33.4	4.3	.000
Cultivated land	3.0	11.4	1.8	3.9	13.2	32.9	4.5	.000
Land/Labor ratio	1.4	5.0	1.1	1.6	6.6	16.0	2.0	.000
%Paddy area	35.5	14.5	4.4	62.0	0.0	3.7	25.5	.000
%Annual crop area	39.5	70.1	59.9	25.3	6.9	37.5	50.1	.000
%Orchard	7.7	10.9	4.6	4.2	75.9	33.9	6.6	.073
Farm's finance								
Total asset	1,786	7,541	1,222	2,429	19,238	31,627	2,888	.000
Production costs	381	2,290	323	352	5,164	11,014	744	.000

Debt	881	4,802	817	959	21,500	25,900	1,674	.000
Power tiller	0.3	0.8	0.1	0.5	1.0	0.6	0.4	.000
Cattle	1.5	1.3	0.7	2.5	0.0	0.4	1.4	.000
Farm income								
Total household income	2,937	8,981	4,450	2,850	32,705	44,750	4,681	.000
Crop income	1,464	7,124	1,007	1,728	11,555	36,807	2,510	.000
%Crop income	53	79	28	65	37	77	52	.000
Low-income off-farm	880	354	2,319	379	0	360	1,177	.000
%Low-income off-farm	29	3	44	15	-	2	26	.000
High-income off-farm	483	1,347	1,046	603	21,150	7,583	879	.006
Livestock income	97	97	40	116	-	-	81	.135
Farm status								
House quality	4.3	5.2	4.1	4.4	8.0	6.0	4.4	.000
Rice deficiency	58.1	44.2	96.8	18.6	100.0	40.0	61.0	.000
Year stay	16.9	15.6	15.6	18.3	18.5	16.8	16.5	.190

Note: P-value is the results of One-Way ANOVA analysis in SPSS for the four farm types excluding the 7 outliers.

The four farm types are distributed unevenly across the ten selected villages. The village characteristics have a strong influence on the relative proportion of farm types. As shown in Table 8, there is a high percentage of Paddy Farms in the Lowland-Diversified Villages and more Smallholder Farms in Upland-Diversified Villages, and Large Farms in the Upland-Intensive Villages. The Off-farm farms are distributed across the three village types especially the two upland ones.

Moreover, the geographic distribution of farm types is linked to the village history and patterns of socioeconomic development in line with its characteristics, such as the size of arable land area. The newly created villages, for example Ou Khmum (2002), tend to have relatively larger and more fertile uplands. In contrast, the old villages, for example Serei Voant (1950s), are mostly paddy-based with high population density since they are accessible thanks to better infrastructure and are safer from landmines for resettlement. As a result, the size of the land allocated to each household is generally smaller than in upland villages.

Table 8: Distribution of farm types and village types

Village type	Sampled village	Type-1 Small holder	Type-2 Large farm	Type-3 Off farm	Type-4 Paddy farm	Outlier 1 Off-farm investor	Outlier 2 Farm investor	Grand Total
Lowland diversified	Kouk Choar	9	1	5	16			31
	Serei Voant	5	5	10	15			35
	Thvak	14	1	8	8			31
Upland diversified	Baribour	11	15	8	2			36
	Chi Pang	11	5	18	1			35
	Phlov Meas	7	4	21	6	1	1	40
	Pich Changva	11	13	2	10	1		37
	Reaksmei Sangha	6	6	19	7		4	42
	Svay Sar	8	8	18	3			37
Upland intensified	Ou Khmum	8	15	16	2			41
Grand Total		90	73	125	70	2	5	365

3.3.3 Farm trajectories

Figure 17 illustrates the process of farm differentiation, i.e. how each type built up over time. The changes in farming systems since the 2000s are identified following the study of Rada Kong et al., (2019). After a full peace agreement and the integration of the Khmer Rouge in 1998, there was a large-scale allocation of degraded forestlands to demobilized soldiers, while the villagers were resettled. We distinguished two groups in the first wave of migration. On one hand were the former villagers or their relatives with paddy production background, considered as Type 4. On the other hand were the demobilized soldiers or their relatives, who decided to make a living with upland crop production despite the risks associated with landmines and malaria in these forested environments. We consider them as Type 1. The size of farmland these pioneer households could secure was defined by different factors: initial **capital and labor availability** that defined their capacity to clear the forest and therefore to secure ownership on that land (Kong et al., 2019), **time of arrival** (i.e. availability of land suitable for agriculture) and **relationship with authorities** (i.e. kinship networks, position in the local administration).

The improvement of road networks and market access changed the farming objectives of newly settled households from subsistence to more market-oriented with soybean and peanut based cropping systems, which also attracted in-migration. The level of income expected from upland farming on fertile soils recently converted from forest encouraged some Type 4 to purchase upland plots after they had accumulated capital from their first years of upland farming and shifted to Type 1. The late comers with capital managed to buy some land in the upland villages and became Type 1 while those who arrived only with their family's labor force contributed to wage labor during the maize boom and formed the farm Type 3.

The introduction of hybrid maize in the mid-2000s amplified the economic differentiation. Farmers who owned large upland areas, accumulated mostly through purchase with initial capital, could further generate capital through maize cultivation that provided a high profit at that time thanks to (i) high soil fertility and low input requirements and (ii) the possibility to cultivate two crop cycles per year with high yields at high market prices. They could gradually enlarge their farmland and buy agricultural and household assets to become Type 2 farmers. The new migrants, who had not enough initial capital but a relatively abundant family labor force, could clear the forestland for others in exchange for the right to cultivate the newly cleared land for the first three years. They used that initial income to purchase the land they had initially cleared for someone else to become Type 1 farmers.

After some years of intensive cultivation, crop productivity declined compounded by the risks associated with irregular rainfall patterns and market price fluctuations (Kong et al., 2019). Risk management strategies of the different household types were investigated by Kong et al. (n.d.) using a role-play game. In the aftermath of the maize boom, risk management strategies through diversification of farm activities with additional farm (crop and livestock) and off-farm activities, for example, and the capacity/willingness to invest in the production of new commodities largely determined the evolution of farm structures. For instance, Type 2 farms invested massively in tree crops (i.e. longan and mango) soon after shifting from maize to cassava. A limited number of the Type 1 farms could step up to Type 2 with additional investments or if they took the risk to take on additional debt. However, some of them and some Type 4 farms eventually stepped down to current Type 3 due to distress land sale following repeated crop failures or sickness of family members. In addition, some Type 2 farms are recent rich migrants, who were originally from the cities or abroad and invested in tree crop plantation.

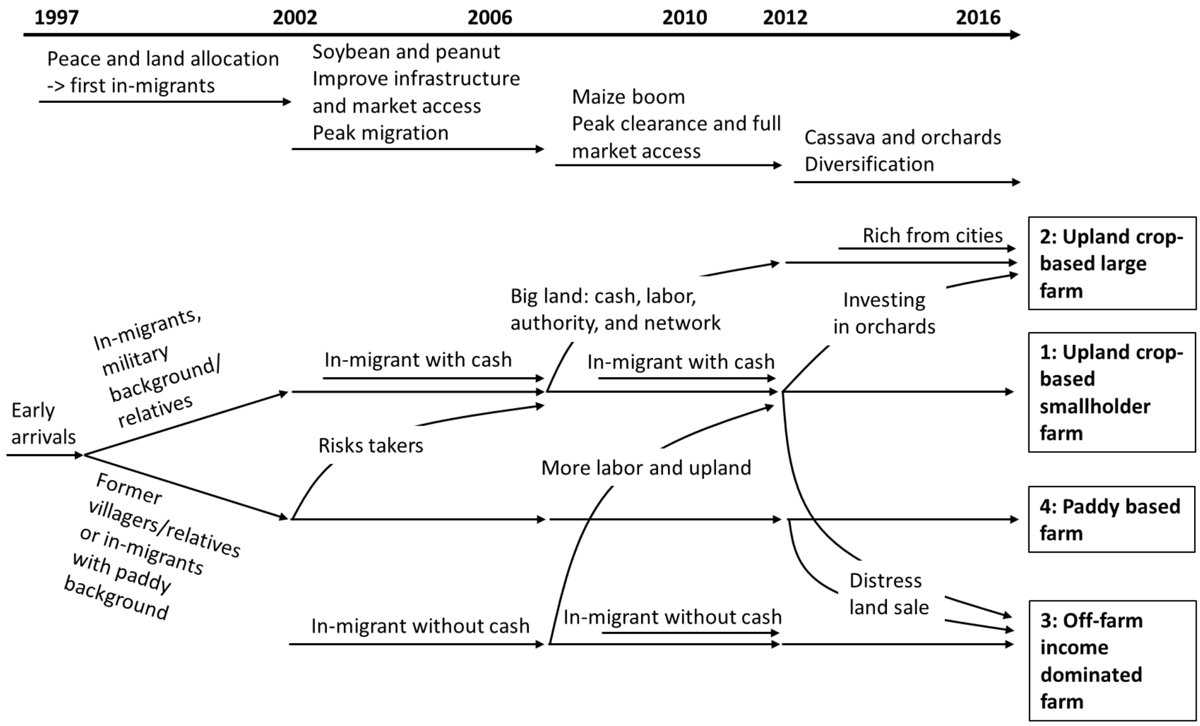


Figure 17: Farm differentiation process and current farm types

3.4 Farming system performances

Our assessment of farm performances focuses on crop production, i.e. the main income source and core to our analysis. The other components of farming systems include livestock systems, off-farm activities and the collection of non-timber forest products. The livestock system, however, consisting mainly of extensive cattle production contributes only marginally to farm incomes (Table 9).

3.4.1 Cropping systems performances

We identified seven cropping systems in Rotonak Mondol District. All farm types practice them on part of their land according to their respective characteristics and trajectories. The economic performances of each cropping system vary with the farm types as presented in Table 9. Among the systems based on annual upland crops, cassava and maize are predominant. However, the large (i.e. Type 2) and small (i.e. Type 3) farms prefer cassava over maize as the former requires less labor and expected productivity is higher. A period of drought at the start of the cycle combined with heavy rains at harvest time and a price drop in 2015 resulted in considerably reduced cassava productivity. The maize-based system with secondary crops, i.e. mungbean, sesame, and peanut, is constrained by high climatic risk (long drought between Feb-June) for the secondary crops, and vegetable expansion is constrained by high labor requirements and price fluctuations. Farms with access to water sources for irrigation and abundant labor force (i.e. Type 4) grow vegetables, and those which have a higher financial capacity (i.e. Type 2) grow more secondary crops. Type 1 and Type 4 farms used to practice the ‘maize plus secondary crop system’; but they have recently abandoned this because of the high risk of failure related to climatic hazards.

Farms with large land and high assets, such as Type 2, have invested in orchard plantations (longan and mango). Type 2 farms tend to have higher production costs in particular due to hiring labor and using chemical inputs and as a result, the labor and land productivities are lower than the other farm types even though they obtain higher yields. For instance, their cassava production obtains 1-4 t/ha higher yield, yet provides about 15-75$/ha less return on land than the other farm types. The lower productivity of cassava is also explained by the fact that Type 2 farms are likely to sell the harvest as fresh tuber while Type 4 and Type 3, which grow on smaller areas, prefer to process the harvest and sell in dry chips for an extra profit.

The yield and production costs of secondary crops are higher for Type 4 since they crop larger areas of peanut. This legume crop may influence the productivity of the following maize crop which yields 0.5 t/ha higher than without a preceding legume crop. Type 4 enjoys higher economic returns on labor as production costs are very low on paddies when compared to Type 1 and larger areas allow them to harvest by combined harvester. Type 2 tends to produce highly intensive vegetables (i.e. drip-irrigated cucumber) while the other types mostly produce low-investment and small-scale vegetables, i.e. wax gourd, pumpkin. In addition, Type 2 generally produces the off-season mango and longan by themselves since they have higher financial capacities for investment and risk management. Other farm types tend to rent out their plantations, in spite of lower profit than direct management, to reimburse rapidly their initial investments.

Table 9: Economic performances of major cropping systems by farm types

			Type 1		Type 2		Type 3		Type 4	
			N	Mean	N	Mean	N	Mean	N	Mean
		Number of plot	90	2.5	73	3.9	125	1.4	70	3.0
		Mean of plot size	184	1.5	170	4.6	141	1.6	165	1.6
Cassava		% HH		40.0		84.6		37.6		35.7
		% Area		17.4		55.4		30.7		10.3
		Production cost ($/ha)	36	207	61	367	48	275	26	231
		Yield (kg/ha)	36	10,007	61	13,796	48	12,966	26	11,316
		Productivity ($/ha)	36	592	61	543	48	555	26	619
Maize		% HH		38.9		34.6		22.4		35.7
		% Area		18.6		11.4		16.4		12.4
		Production cost ($/ha)	40	95	43	124	37	104	30	89
		Yield (kg/ha)	40	3,347	43	3,911	37	3,010	30	3,656
		Productivity ($/ha)	40	424	43	526	37	592	30	585
1st cycle crop / Maize	1st cycle crop	% HH		13.3		19.2		8.0		12.9
		% Area		4.3		4.8		3.3		3.1
		Production cost ($/ha)	15	85	21	72	11	61	12	90
		Yield (kg/ha)	15	268	21	326	11	223	12	822
		Productivity ($/ha)	15	164	21	179	11	198	12	498
	Maize	Production cost ($/ha)	15	109	21	104	11	117	12	133
		Yield (kg/ha)	15	3,506	21	3,638	11	3,654	12	3,947
		Productivity ($/ha)	15	403	21	509	11	427	12	617
Paddy		% HH		68.9		53.8		7.2		100.0
		% Area		35.9		11.9		3.2		56.0
		Production cost ($/ha)	62	128	44	106	9	110	68	87
		Yield (kg/ha)	62	1,338	44	1,804	9	864	68	1,526
		Productivity ($/ha)	62	168	44	305	9	66	68	254
Vegetables		% HH		6.7		3.8		4.0		8.6
		% Area		2.4		0.5		2.0		0.7

	Production cost ($/ha)	6	123	5	1,175	5	1,118	6	2
	Yield (kg/ha)	6	15,318	5	35,869	5	15,463	6	15,723
	Productivity ($/ha)	6	4,510	5	7,059	5	3,859	6	5,303
Longan	% HH		13.3		23.1		5.6		15.7
	% Area		4.9		8.5		2.2		2.1
	Production cost ($/ha)	12	3	18	94	7	23	11	66
	Yield (kg/ha)	12	4,702	18	3,279	7		11	7,222
	Productivity ($/ha)	12	1,299	18	912	7	-23	11	1,139
Mango	% HH		8.9		15.4		6.4		7.1
	% Area		1.8		2.6		3.0		1.1
	Production cost ($/ha)	8	0	13	7	8	5	5	5
	Yield (kg/ha)	8	1,216	13	862	8	25,000	5	1,333
	Productivity ($/ha)	8	507	13	58	8	986	5	28

3.4.2 Farm income composition

Crops and off-farm activities provide the bulk of farm income (Figure 18). The main income sources are from annual upland crops (cassava and maize) for Type 2 while off-farm activities, in particular for the low-income farms, provide a large share of household income for Type 3. Type 1 and Type 4 have rather diversified income sources. The strategy of Type 4 is to maintain a safety net with the integration of rice production and cattle raising while generating cash income from off-farm activities and annual upland crop cultivation. This type tends to minimize the production costs of chemical inputs and services by relying on manual cropping practices thanks to an abundant family labor force. With smaller paddy areas, Type 1 intensified annual upland crop cultivation and invested in off-farm, especially low-qualified, activities. Type 2 has the most intensive farming system. Their strategy is to intensify land use through mechanization, input use and innovative techniques, then to expand orchard areas and diversify their income with high-income off-farm activities. In contrast, the strategy of Type 3 is to focus on off-farm activities paying high wages, particularly migration work in Thailand. Therefore, their cropping practices aim at saving labor and inputs through cultivation of cassava and orchards.

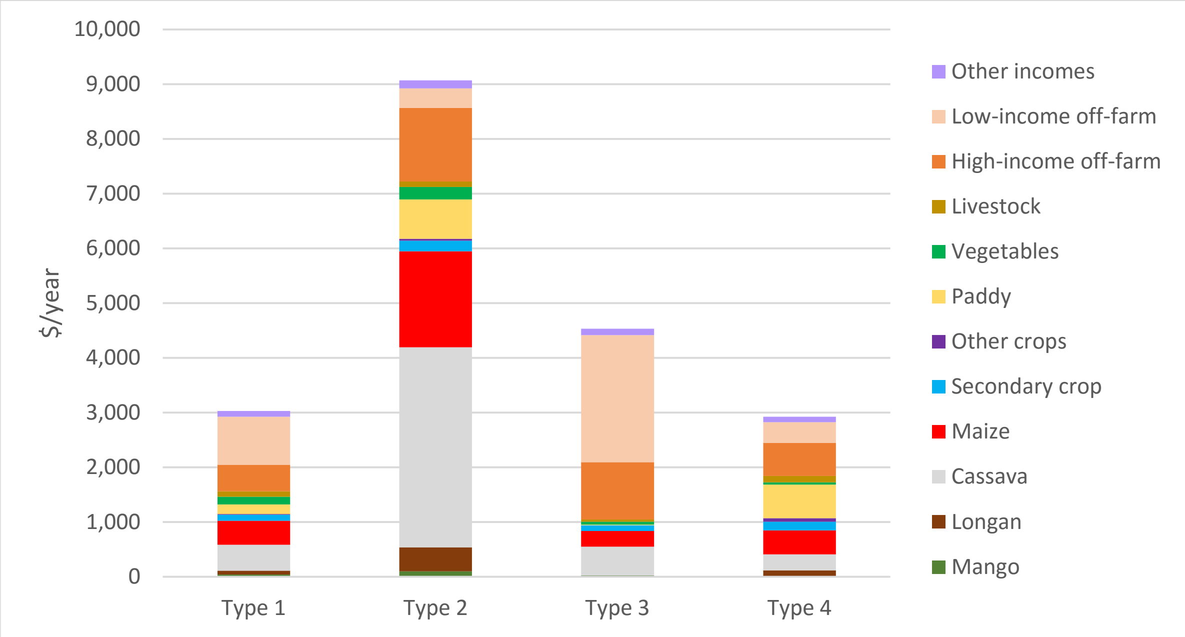


Figure 18: Sources of farm income and livelihood activities

3.5 Farm structure and capacity to innovate

3.5.1 Adoption of innovations

Farmers constantly test small changes in their cropping systems and their robustness to weather uncertainty, price fluctuations and soil fertility depletion. For example, they stopped the double maize cycle after a few years, as the first maize cycle was too risky and dependent on the irregularity of the first rainfalls. They then replaced the first cycle maize by a legume crop (mungbean or peanut) which gave good results on low-elevation hydromorphic soils but was too risky on higher-elevation soils. On this higher part of the topo-sequence, they finally adopted a later cycle of mungbean after maize to better valorize residual soil water at the end of the rainy season. The number of innovations tested by farmers increased after 2010 when a project of the Ministry of Agriculture, Forestry and Fisheries promoted conservation agriculture in the study district (R. Kong et al., 2016). The project introduced farmers to the use of cover crops, no-till and no-burn as well as improving pasture as options for sustainable land management. From 2012, new crop rotations were tested with maize and cassava, and the intercropping of vegetables, maize or cassava in orchard plantations emerged as reactions to the observed decline in maize productivity.

The percentage of innovative households (i.e. those who had adopted one of these innovative practices) reached a peak in 2015 and then decreased dramatically the following years, in particular those related to crop successions and rotations. The climatic risks for the 1st cycle crops and high price fluctuations for maize both explain the drop. Conservation agriculture techniques (Kassam and Friedrich, 2012) aim to rebuild soil functions and resilience to climatic risks through growing cover crops during unfavorable conditions as rotational or succession systems with the main crops. These cover crops provide agronomic services to the main crops, but their adoption is also guided by commercialization purposes such as the 1st cycle crops. In short, farmers are more eager to adopt them if they can sell their products.

There is a higher number of Type 2 farms which innovate, tending to test a larger number of innovations (Figure 19), especially no-till and no-burn, cover crop integration, crop rotation, and orchard intercropping. They explained this capacity to innovate during the in-depth interviews and the role-play games by their higher farm resources, capacity to take risks and willingness to change for the better (Kong et al., n.d.). Type 1 farms have similar characteristics in terms of adoption and willingness to innovate as Type 2 but lower capacity to take risks because of their limited resources. In contrast, Type 3 has the lowest percentage of innovation due to their farm constraints related to land and financial capital, and also time constraints as most of their labor force is dedicated to off-farm activities. However, they have, like Type 4, a high involvement rate in farmer organizations, mainly focusing on savings and credit. With a greater number of cattle, Type 4 adopted improved pasture early on and with a higher percentage of farmers than other farm types. They also have lower drop-offs in crop succession (i.e. double cycle cropping) since their fields are located in the lower part of the topo-sequence, thus less vulnerable to drought. They also have a greater farm labor force.

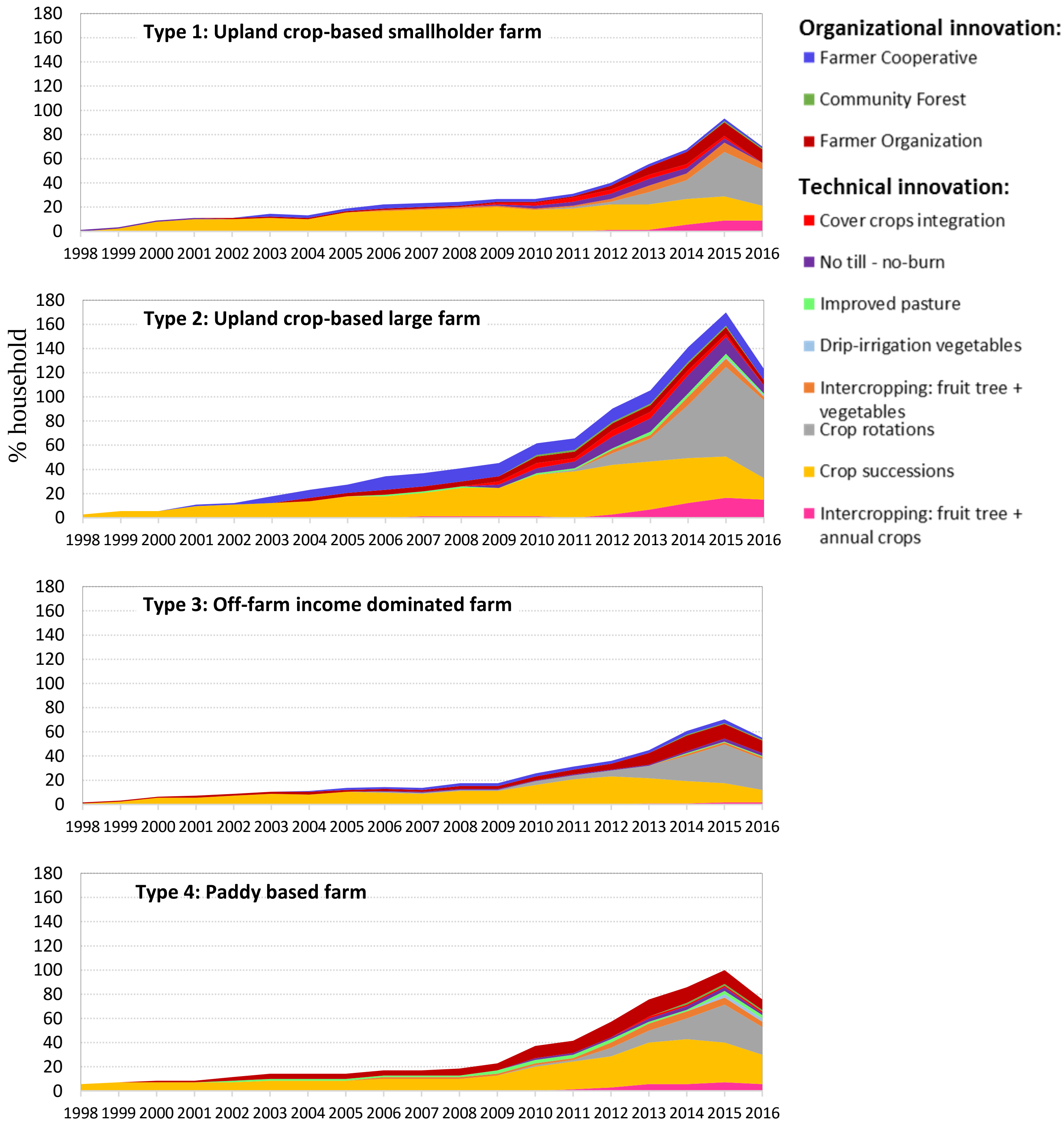


Figure 19: Evolution of innovation adoption from 1998 to 2016 per farm type

3.5.2 Leverages for innovation

The room for maneuver and capacity to improve performances are different for each farm type since they have different constraints, strategies, expectations, and trajectories. Central to their capacity to innovate are (i) risks management, (ii) sustaining labor productivity and (iii) diversifying farm income.

Type 1 and Type 4 farms already have a diversified activity portfolio to buffer the risks from rainfall variability and market price fluctuation. Agroecology practices could enhance farm productivity, i.e. return on land, labor, and capital, through integrated management of all components of the farming system: paddy, cattle, and vegetable production in the lowlands and intercropping and agroforestry in the uplands. For instance, including a service crop, i.e. *stylosanthes guianensis,* in the rice cropping systems can improve the fertility as well as the rice yield and also produce good quality forage for the cattle fattening program (Tivet and Boulakia, 2017). Besides providing energy, the rich compost from the biogas of cattle manure and urine is used for vegetable production (Warnars and Oppenoorth, 2014; Hyman and Bailis, 2018). Promising options for the uplands could take the form of rotational systems based on maize, cassava, and soybean with relayed secondary crops such as mungbean and pigeon pea, commercial forage production, and/or intercropping of agroforestry systems with orchards and vegetables.

The appropriate scale mechanization for agroecological intensification is highly appreciated by resources-rich Type 2 farmers, who are constrained by the availability of farm labor to engage in larger scale production. Rotational cropping systems combined with permanent cover crops in orchard plantations are prioritized by Type 2 farms. A possible diversification pathway would include improved pasture and rotational grazing with solar electric fences for cattle production, and agroforestry systems with luxury timber trees. Mechanization efforts and more generally labor saving technologies provided by service providers are highly appreciated by resource-poor farms such as Type 3, which are highly constrained by farm labor and capital. For example, this farm type showed great interest in agroforestry systems, including orchards with permanent cover crops and forage production (Tran Quoc, 2018).

The above-mentioned technical innovations are systematically associated with organizational innovations, which involve collective learning and sharing of knowledge on the common problems faced by agroecological intensification, especially those related to market access, access to production factors (especially through credit), and service provision by middlemen for agroecological practices (Lestrelin et al., 2019). To succeed, stakeholders involved in the crop value chains have to develop coordination mechanisms, for example to establish the market guarantee systems through contract farming with private companies (Begum et al., 2014; Kyomugisha et al., 2018; Sum and Khiev, 2015). Likewise, for access to the agricultural services, the outliers, who own large plantation and machines, could join with Type 2 farms to provide agricultural services to other farm types. Many such initiatives already exist on the ground. They still need to be properly documented and supported to engage local innovators in an agroecology-based innovation system.

3.6 Discussion

3.6.1 Farm typologies and trajectories: advantages and constraints

Understanding farm diversity with its characteristics, constraints, and opportunities is essential for supporting the sustainable development of farming systems (Giller et al., 2011). Farm typologies are widely accepted as a simple and efficient tool to understand the complexity of farming systems. The approach to build farm typologies has been gradually improved and enriched by research communities so as to adapt to different purposes and local contexts (Alvarez et al., 2014; Alvarez et al., 2018). Typology variables can be selected for instance in relation to water resource management for irrigated rice production, or cropping practices that control certain pests or improve water use efficiency and productivity. The main objective of farm typologies is to cluster farm households with similar characteristics of farm endowments, resources, structures, livelihoods, land use intensity, etc.

Our approach to farm typology aims to explain the evolving diversity of farming systems in a context of rapid land use changes. Our structural typology (Tittonell, 2014) builds on multivariable statistical analysis combining principal component analysis (PCA) and hierarchical cluster analysis (HCA) with discrimination variables related to the history of settlement, farm resources, structures, land uses, livelihood activities and economic performances. Within each element, 12 key discriminating (slow moving variables) and functional (fast moving variables) variables (Berre et al., 2016; Lopez Ridaura and Tittonell, 2011) (Table 6) are finally selected based on both expert knowledge and a series of tests on different combinations of the 27 variables. This approach yields a typology explaining how differences between household types build up in time.

In addition, we conducted retrospective interviews with a randomly stratified subset sample of each identified farm type to understand the trajectories of farm resources, activities, land uses, and innovations. Understanding farmers' reasons for changes and their decision making process led to a soft, functional perspective that helps explain the statistical relations between variables provided by the structural typology (Alvarez et al., 2014). By analyzing the spatial distribution of farm types and relations to the biogeographical characteristics of their villages, we could explain the local patterns of farm resources, socioeconomics and biophysical conditions. Our approach is therefore complementary to previous typologies based on the qualitative method in the Northwestern Uplands of Cambodia (Diepart and Sem, 2018; Yoeu, 2016). More importantly, our approach includes the relations between farm types and their capacity to innovate. It captures different farm types' decision making processes and their capacity to innovate as a basis to co-designing appropriate innovation and intervention mechanisms.

The main limitations of our approach lie in the retrospective analysis of farm trajectories and the validity of the farm typology over a long time period in a context of rapid changes. The previous typology done in 2010 by Bertrand (2011) included only two of the ten sampled villages. It could therefore not be used as a baseline for a longitudinal analysis of the dynamics of farm differentiation, i.e. how and why farm types evolve in time (Jiao et al., 2017). Despite the explanation provided through qualitative in-depth surveys, the typology is constructed using multivariate statistical techniques (Kuivanen et al., 2016a) and therefore provides a snapshot in a given time (Laurent et al., 1999) and thus its validity is limited in time. Nevertheless, our data may serve as baseline for a longitudinal analysis, and would provide a comprehensive approach to farm trajectories over a longer period.

3.6.2 Dealing with impermanence in assessing farm diversity

Farming systems are not static; they are rather a moving target (Giller et al., 2011). Due to the rapid dynamic in particular in the context of forest frontiers and boom crops (Hall, 2011), the typology could soon become out of date, and would thus need to be regularly updated to maintain an understanding of a farm's diversity (Valbuena et al., 2015). In addition, forest frontiers, pioneer fronts and borderlands are characterized by rapid changes in the absence of a regulatory framework. Governance systems are weak and local institutions evolve rapidly in a context characterized by impermanence. Capturing changes in farm diversity becomes a challenge in such a context.

Our approach based on structural typology could capture this diversity, but it is not stable over time and is highly context dependent while under the strong influence of the globalization of markets, technologies and institutions (Dixon, 2018a). For instance, a longitudinal study of rural livelihoods in Cambodia from 2008 to 2012 found that more than 70% of households changed their livelihood strategies to more remunerative ones in response to evolving pressures, incentives and opportunities (Nguyen et al., 2015). Dixon (2019) advocates for using a functional household typology based on farming systems, household strategies, and a farm's biophysical characteristics. A typology with a long-term validity helps to better target intervention policies as well as agricultural development programs. Expert-based typologies with involvement of the local stakeholders could also be useful since the typology is based on functional variables, for example resource endowments and the biophysical characteristics of farm land (Landais, 1998).

In our study area, an expert-based typology would lead to three main farm types, i.e. low to medium resource endowment paddy based farms, low to medium resource endowment upland based farms and high resource endowment upland based farms. These types would be relevant during the maize boom in late 2000s but not beyond that time as strong and rapid land use changes influenced by external factors had tremendous impacts on the farm structures. Our four farm types are likely to remain the same in 5 to 10 years from now. Significant changes may happen in the relative proportion of each farm type, in particular in the upland based villages. Type 1 and Type 2 are the most impacted by these changes. The risks of market fluctuations and climate hazards are likely to increase the proportion of Type 3 farms and possibly lead to the emergence of a new type stemming from Type 2. This new type would be characterized by large-scale agricultural production (likely orchards) with a high level of intensification based on advanced technologies.

Another way to secure a long lasting typology is to select only “slow moving” variables for the multivariable statistical analysis (Berre et al., 2016). To increase the typology relevance, we could take out the “fast moving” variables such as economic performances (income and its share) and keep fewer “slow moving” variables including farm structure, farm resources, and physical characteristics of farm land as done by Falconnier et al. (2015). This is a compromise between the duration of typology validity and the comprehensiveness of farming system diversity.

3.6.3 Perspectives toward land conservation practices

Our farm typology approach prioritizes intervention mechanisms adapted to each farm type, and also adjusts innovations to farmers’ perspectives on land conservation practices. The discriminating variables characterize farm types according to their resources, structure, functions, performances, constraints and opportunities, as well as their capacity to innovate. The technical innovations such as no-tillage, no-burning of crop residues, cover crops, crop rotational systems, etc. are land conservation practices. There is a relationship between farmers’ capacity to innovate and their adoption of soil conservation practices.

The farm types which are the most impacted or at risk of economic or climatic hazards, such as Type 1 and Type 2, tend to show more interest in land conservation practices. In contrast, Type 3 and Type 4 farms opt for conservative strategies since their livelihoods depend primarily on less risky activities such as off-farm activities and paddy production. Although Type 4 farms own more land than Type 1, they are not willing to invest in land conservation practices unless there is no extra cost and/or additional labor required. Type 3 are less committed than Type 4 in soil conservation since they own too little land and have no financial capacity to invest. Yet, they are willing to adopt any innovation that could save labor whether it relates to land conservation or not.

Type 1 and Type 2 are willing to adopt soil conservation practices as their livelihoods are more dependent on farming activities, and thus are more affected by a decline in land productivity. Restoring land fertility and ecological functions through sustainable intensification (Kassam and Friedrich, 2012; Campbell et al., 2014; FAO, 2018) could buffer the negative impacts of climatic hazards and increase their adaptation to rapid changes in their production environment. Generally, farms with high resource endowments such as Type 2 and Outlier 2 have a relatively higher capacity to manage risks. Their adaptation mechanisms combine high assets and financial capacity with diversified income sources, both agricultural and off-farm (Kuivanen et al., 2016a). Therefore, they are the most advanced in innovation processes since they test a large number of technical and organizational options. Kong, (n.d.)

found that these farm types (Type 1, Type 2, and Outlier 2) predominantly experiment with conservation agriculture techniques. The on-farm researchers should consider them as a "farmer-innovators" and work closely with them in co-designing soil conservation practices (Husson et al., 2016).

3.7 Conclusions

Combining multivariate statistical analysis and analysis of the historical changes and decision-making processes, this study identified four main farm types (smallholder farm, large farm, off-farm, and paddy farm) and two types of outliers (off-farm investor and farm investor). This farm typology approach helped understand farm diversity through the characterization of the distribution in time and space of the farm's structures, functions, and performances. We found that the capacity to innovate is strongly linked with the risks encountered and individual capacity to manage them, according to farm resource endowment, diversified land uses and opportunities for off-farm activities. The higher the capacity to manage risks, the more willing they are to experiment new techniques and to innovate. The study could serve as a baseline for a longitudinal study on the dynamics of farming systems in a context of reorganization of the agricultural systems after a period of pioneer front. The set of variables used in this study on farm characteristics including the farm's resources, structure, functions and biophysical features combined with an analysis of farmers' decision-making process provide new insights into the use of farm typologies in a context of agricultural innovation.

Acknowledgements

The author would like to thank Jean-Christophe Castella, Florent Tivet, and Jean-Christophe Diepart for their advice and comments on earlier versions of this manuscript.

Chapter 4

Investigating farmers’ decision-making in relation with the adoption of conservation agriculture in the Northwestern uplands of Cambodia

Abstract

In the Northwestern uplands of Cambodia, the commodification of agriculture of the 2000s substituted the traditional rotational and diversified cropping systems with monocropping of commercial crops such as maize and cassava. Land degradation observed after a few years intensive monocropping undermined the sustainability of the overall agricultural system. However, the promotion of soil conservation practices is challenging in such a context. We developed a model of Land Use/Cover Change by integrating results from analysis of the time series of remote sensing data, farming systems diagnosis and a review of a project promoting conservation agriculture (CA) techniques since 2010 in Rotonak Mondol District, Battambang Province. The model was used to co-design with villagers a role-play game named “Resilient Agriculture through Co-Design of Agroecology Pathways” (RADA).

The game revealed that market opportunities and high, short-term economic returns are key parameters in the process of farmers’ decision-making. While waiting for a new boom crop to emerge, the farmers, in particular in the CA villages, are willing to adopt soil conservation practices and diversify their farms’ activities. The study shows the importance of opportunity windows for intervention, the involvement of farming communities in co-designing alternative cropping systems and the importance of social organization in learning to bring CA to scale.

This chapter is based on the following research article:

Kong R., Castella J.C., Tivet F., Diepart J.C., Leng V., Suos V., Pat S., Sen R. Investigating farmer’s decision-making in relation with the adoption of conservation agriculture in the northwestern uplands of Cambodia. Under review *Ecology and Society*

4.1 Introduction

4.1.1 The challenge of promoting sustainable land management practices in a context of rapid land use changes

Within a few decades, intensive monocropping practices replaced traditional upland agriculture based on shifting cultivation, which historically prevailed across Southeast Asia. The high market demand for crops such as maize and cassava for feedstock or biofuel has driven this rapid conversion of smallholder production systems from a subsistence to a market orientation, in a phenomenon also known as the commodification of agricultural systems (Cramb et al., 2009; Ingalls et al., 2018b). Thousands of upland farmers gradually switched from rotational cropping systems that had shown their capacity to maintain soil fertility and biodiversity under low population densities to intensive cash crop monocropping. This dramatic land conversion was associated in many places with deforestation, erosion of soils and biodiversity as well as pollution from increasing use of chemical inputs that gradually undermined the sustainability of the upland farming systems. Within just a few years, the initial benefits of low-input cash crop production on former fallow fields and forests decreased significantly. As a result, the production of these agricultural commodities became less economically attractive for smallholder farmers, which led them to abandon the newly adopted crop commodities. This bust phase associated with soil organic matter depletion and economic loss appears to be an inevitable stage after the crop boom (Hall, 2011).

To overcome yield loss due to the soil organic matter depletion, an easy solution for sector actors is often to move the intensive cropping systems to new locations along rapidly advancing pioneer fronts, where the natural resources are still relatively abundant. Through that displacement process, the same land use dynamics are reproduced in different locations across the region. Little learning from previous failures leads to repeated 'boom and bust' scenarios (Hall, 2011; Ornetsmüller et al., 2018). Once upland farmers have turned their complex landscape mosaics into permanent crops, returning to shifting cultivation systems is no longer an option. Many are then hoping for a new boom crop to replace the previous one, despite knowing that such alternative crops will not provide any long-term perspective on agricultural intensification.

A crop prone to booms is in high market demand for large volumes of production, easy to grow (i.e. maize like cassava are flexible as the ripe crop can be left several weeks in the field before the harvest), and with inputs and services provided on credit by agribusiness companies or intermediaries. These crop characteristics represent major challenges for researchers and extension agents who promote sustainable agriculture intensification. Studies of farmers' adoption of conservation agriculture have shown that little adoption occurs during crop booms, as many farmers do not consider the negative impacts of their practices on the environment until land degradation leads to yield losses and decreasing economic returns (Castella et al., 2012).

To maximize the adoption of sustainable intensification practices such as conservation agriculture, a better understanding of farmers' decision-making processes is definitively required. Ideally, this should be part of a joint effort between farmers and promoters of sustainable intensification to learn about the ins and outs of successive boom-bust cycles. This is a necessary condition to help engage with farmers in co-designing options for sustainable intensification of cropping systems. This article tells the story of an initiative in the Northwestern uplands of Cambodia which went beyond understanding farmers' decision-making in order to engage with them in social learning through a gaming approach.

4.1.2 Promotion of conservation agriculture during the maize boom of the 2000s in the Northwestern uplands of Cambodia

Kong et al. (2016) reported such an attempt to promote alternative cropping systems during the maize boom of the 2000s in Battambang Province located in the Northwestern uplands of Cambodia (Figure 20). From 2005 to 2015, this region underwent massive land conversion from forest to agriculture, mainly driven by maize expansion (Kong et al., 2019). Agricultural expansion was driven by market demand and the high profitability of maize, vast available forestland with weak land governance and spontaneous in-migration of poor and landless farmers from highly populated lowlands. Rapid land use changes were driven by the decisions made by individual farmers, which in turn have deeply affected their livelihoods. More recently, the agricultural expansion also attracted rich farmers and entrepreneurs attempting to take advantage of the boom (Kong et al., 2019).

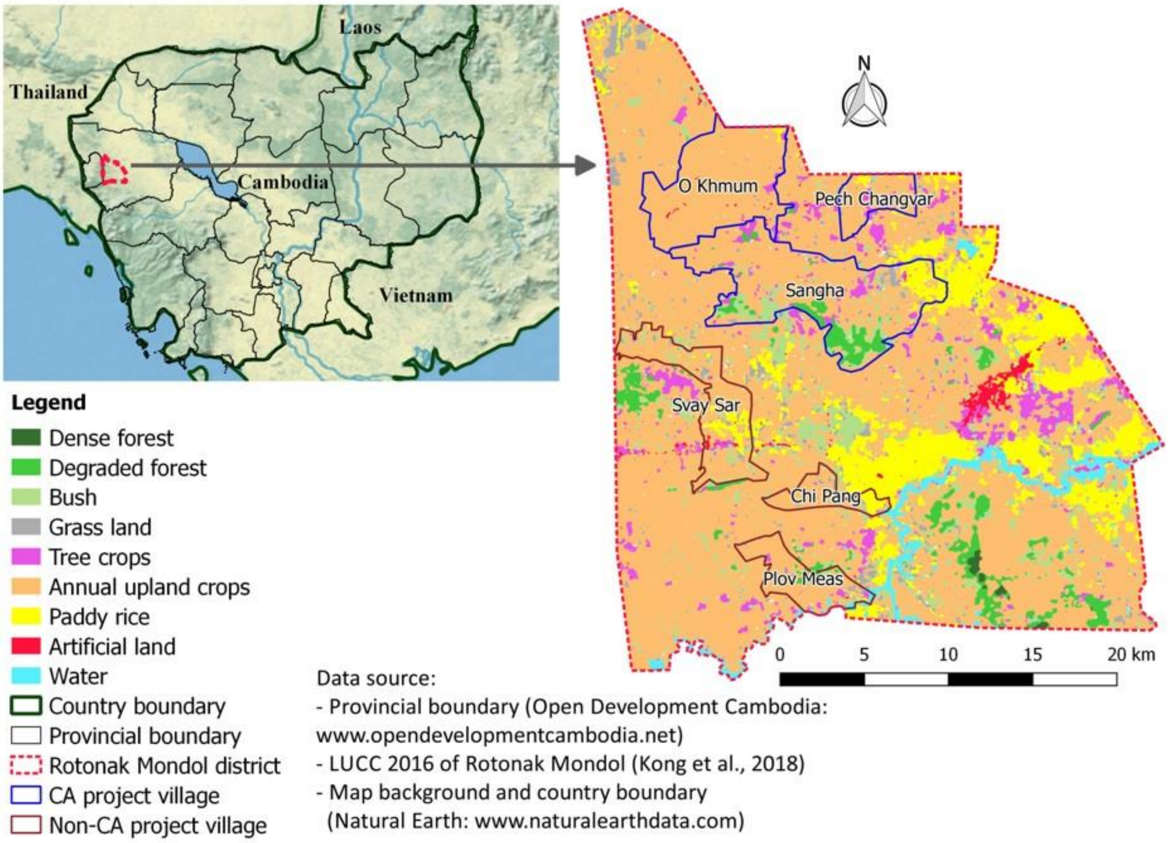


Figure 20: Study area in Rotonak Mondol District, Battambang Province, Cambodia.

Concerned by the negative impacts of the rapid maize expansion on the sustainability of upland farming systems, the Ministry of Agriculture, Forestry and Fisheries (MAFF) with technical support from CIRAD and financial support from the French Agency for Development (AFD) and the United States Agency for International Development (USAID) initiated a research for development project on Conservation Agriculture and Direct Seeding Mulch-Based Cropping (DMC) systems (Husson et al., 2016). These are based on three technical principles: (i) minimizing soil disturbance; (ii) covering the soil permanently with plant cover; and (iii) diversifying crops and cover/relay crops species through rotations, succession and/or association (Kassam et al., 2018). The project was implemented in four villages of Rotonak Mondul District, Battambang Province (Figure 20). Agronomists engaged with local farmers in co-designing CA-based cropping system in order to: (i) increase the maize productivity; while (ii) preserving soil fertility and biodiversity; and (iii) increasing the resilience of the agricultural production systems to economic fluctuations through diversified income sources. A multi-scale, multi-stakeholder, participatory approach called DATE - Diagnosis, Design, Assessment, Training and Extension (Husson et al., 2016), involved researchers, extension agents and farmers in successive learning loops.

In 2010, the diagnosis phase of the DATE approach showed the essential role that maize played at the farm and landscape level as it was almost the only crop planted during the wet cropping season. Mungbean, sesame, and maize were cultivated as preceding crops from February to June (dry season crop cycle) under plow-based management and herbicide use, without use of organic or inorganic fertilizer. Consequently, the fertility of shallow mollisoils depleted quickly, and crop productivity declined with strong negative impacts on farmers' income partially compensated by crop expansion on forestland at the initial stage of the maize boom.

Based on the results of the initial diagnosis, improved maize-based cropping systems were developed and tested on-farm (1st loop). Maize association with cover crops, i.e. stylo (*Stylosanthes guianensis*), rice bean (*Vigna umbellata*) and pigeon pea (*Cajanus cajan*), emerged as a promising option and was then included in a farm demonstration network (2nd loop). Technical and economic performances were jointly assessed with farmers and extension agents before the new cropping system was proposed in a pre-extension network (3rd loop).

To support farmers' adoption of CA practices the project provided a subsidized package including: (i) supply of cover crop seeds for free; (ii) maize yield guarantee of 4.5t/ha; and (iii) an interest-free credit of 250-300 $/ha on CA services and fertilizers. Farmers could use the credit to cover costs related to rolling services and herbicide spraying to terminate the cover crop, a no-till planter, and chemical fertilizers. The subsidy aimed at optimizing the agronomic and economic benefits of the proposed CA systems at the initial adoption stages. Beyond these incentives, the project collaborated with an international NGO to support farmers' training and enhanced coordination among stakeholders. Farmers' organizations, agro-industries and microfinance institutions, engaged in the innovation process.

Farmers who engaged in the project on a voluntary basis agreed to apply the technical package including advisory services and field coaching, and to reimburse the credit according to the attained yield after the harvest. These incentive mechanisms lasted during the period from 2010 to 2012. After subsidy withdrawal in 2013, the project continued to provide technical advice through extension agents and no-till sowing services for a fee similar to that of private contractors in the area ($35/ha for maize sowing). Consequently, CA farmers are defined differently according to the period. During the subsidy period (2010-2012), CA farmers were those who implemented the technical package promoted by the project in any field of their farm. After the subsidy withdrawal, CA farmers were those who hired CA services, namely to sow with a no-till planter on any field of their farm.

The CA area increased gradually in the four target villages of the project to reach a peak in 2014 with 290 ha and 84 households (Figure 21). During the initial evaluation of the project in 2014, the results were very promising in terms of adoption and impacts on sustainable maize production (R. Kong et al., 2016). However, the CA area dropped dramatically in the subsequent years to only 140 ha with 27 households in 2016. Low profitability of maize (i.e. labor and land) and higher market prices of cassava at that time provoked this change.

However, the unexpected decrease of cassava profits in 2016 due to a long drought spell in the early stage of plantation which increased replanting costs, sharp price decreases, and lower yields after 3-years of monocropping encouraged the farmers to re-balance the cultivated area in 2017 with maize. The CA area thus reached about 270 ha with 94 households. When the subsidy mechanism stopped in 2013 adoption rates still increased while at the same time the drop-off rate also increased. However, drop-off reached a peak in 2015 with about 65% farmers stopping CA practices (Figure 21). More recently, CA adoption increased again through mechanisms that remain largely unknown.

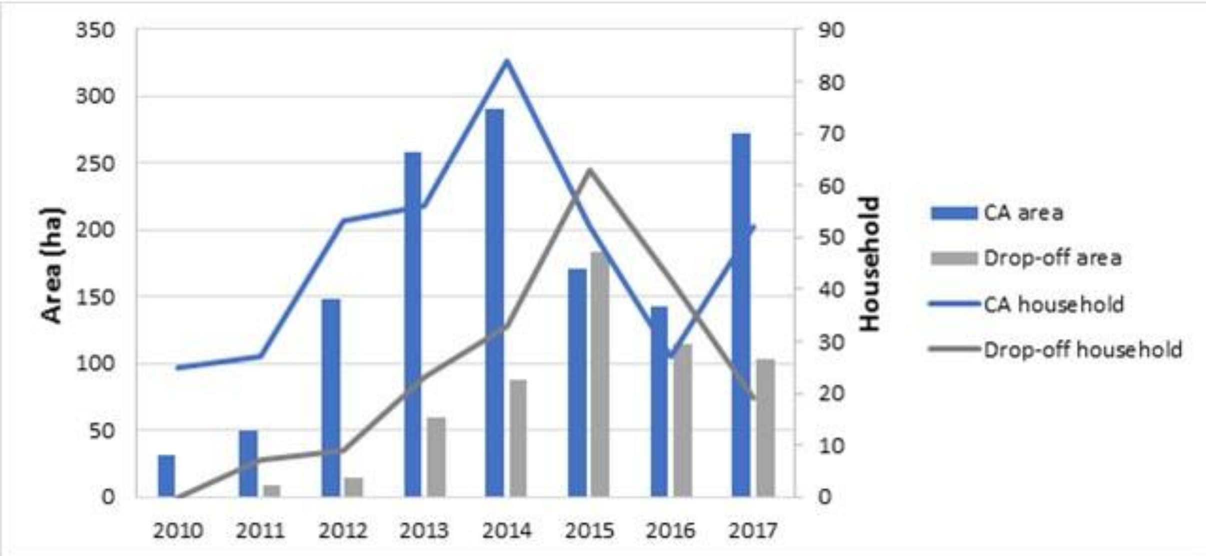


Figure 21: CA evolution from 2010-2012 with subsidy and from 2013 without subsidy

These results raised a number of questions concerning farmers' decision-making in relation with adoption of sustainable land management practices in a time of rapid land use changes. While the project proponents have already addressed these questions during the project evaluation phase (R. Kong et al., 2016), we propose in this paper to address them from the perspective of the project beneficiaries, including the CA farmers and drop-off farmers (i.e. who adopted CA at some stage and then abandoned it). An insider's perspective may help adjusting the co-design process to farmers' views and interests. Better anticipating future changes would also be useful to keep agronomic research relevant despite very rapid land use changes and orient future intervention mechanisms for higher impact.

In this paper, we report on the process of designing the game and the results of the game conducted with local farmers in CA and non-CA villages. We then investigate how decisions were made in the past and how they could be influenced in the current settings to orient land use trajectories towards more sustainable practices. Finally, we analyze the conditions of adoption of CA techniques for farmers with different resource endowments, constraints and strategies and draw lessons on how to support innovation processes such as CA in context of rapid land use change.

4.2 Methodology

Rotonak Mondol District was selected as it is representative of the pioneer front in the Northwest of Cambodia (Figure 20 and (Kong et al., 2019) and because it is where the CA project has been implemented since 2010 (R. Kong et al., 2016).

4.2.1 Using a role play game to investigate decision making in land uses and adoption of CA innovation

Studying farmers' decision-making in a context of project intervention was challenging as some of the project proponents were involved in the evaluation, and therefore individual surveys or focus group discussions may be biased. The decisions under study were made in the past, and a retrospective analysis is difficult as people are not in the same mindset as when they decided to adopt, not to adopt, or to abandon CA practices in the early 2010s. We therefore chose to use a gaming approach to investigate farmers' decision-making related to land conversion and adoption of sustainable land management practices such as CA.

A gaming approach was expected to favor interactions among stakeholders and put farmers in the situation they were in when they took their decisions related to CA adoption a few years prior. We would then be able to engage in discussions concerning their perception in the specific context of the period of the maize boom and their individual villages and households' trajectories. Their attitude during the game was also expected to reveal much more about their decision-making process than face-to-face interactions through formal questionnaire surveys that had already been administrated during the project evaluation (R. Kong et al., 2016).

The role-playing game (RPG) is used to elicit knowledge from local actors and also as a support tool for negotiations between different stakeholders to reach a collective decision. It has been used widely in recent years to manage conflicts in the uses of common resources and for common understandings on social-ecological systems in the sustainable management of natural resources (Etienne, 2014). In addition, RPG has proved to be a powerful learning tool for both the players (actors) and the game organizers (researchers) since the players could be placed in real-life situations for them to react or interact among themselves to a proposed scenario (Barreteau et al., 2013).

In our case, designing the RPG was also used as an approach to integrate knowledge from different sources, namely a remote sensing analysis of LUCC (Kong et al., 2019), an ex-post evaluation of the pilot CA project, a survey of farming system diversity and cropping practices and statistical data available at different administrative levels. Our approach aimed at addressing three key research questions:

- How do farmers with different resource endowments, constraints and strategies perceive CA techniques and react to the project's approach?
- What external factors (market, institution, policies…etc.) influenced farmers' decision-making?
- What lessons can we draw on promoting CA in a rapid land use change context?

4.2.2 Knowledge integration from multiple sources and scales

We integrated knowledge from different sources, topics and scales into a role-playing game centered on a farmer decision-making model. The collaborative process of model design relied on pre-existing reports and data as well as on expert knowledge of resource persons who were invited to take part in the design process (Figure 22).

4.2.2.1 The land use change analysis

A previous study by Rada Kong et al., (2019) investigated the trajectories of land use change in a study area that included the Rotonak Mondol District by combining an analysis of a time series of remote sensing data over a 40-year period with actor-based interpretation of the drivers of change. Proximate causes and underlying factors of LUCC were validated using secondary data and focus group discussions. Village data was extracted from the communal database to classify the 38 villages of the district according to their characteristics (Kong, n.d.).

4.2.2.2 Farming system analysis

Ten villages were selected from stratified random sampling according to the four village types identified during the previous step, namely: Urban Village, Upland-Intensified Village, Lowland-Diversified Village and Upland-Diversified Village (Appendix 11). An individual survey was applied to 365 households randomly selected from these 10 villages. A quantitative questionnaire addressed the main characteristics of their farm structure and cropping practices; a household typology was then produced from this dataset. A detailed description of the four farm types: Upland crop-based smallholder farm, Upland crop-based large farm, Off-farm income dominated farm, and Paddy-based farm, is provided in Appendix 11. From these, 95 households were finally selected from stratified random sampling and in-depth, semi-structured interviews were conducted to investigate land use trajectories of individual farms and their drivers, and to assess the technical-economic performance of existing cropping systems / land uses in the district.

4.2.2.3 Adoption of CA practices

Relevant documents of the CA project were systematically reviewed. A specific survey concerning the reasons of adoption or abandonment of CA practices was then conducted with 165 households in four target villages of the CA project (O Khmum, Pich Changva, Reak Smey Sangha, and Baribou). In-depth interviews were conducted with two different groups of farmers who had experienced CA practices. Some households were the same as the ones surveyed previously as part of the analyses on land use change and farming systems. The details of surveyed villages and households are presented in Appendix 12. The surveys addressed two separated periods, subsidies from 2010 to 2012, and subsidy withdrawal from 2013. Continued CA farmers are those who engaged with the subsidy package agreement during the subsidy period and/or those who, after the subsidy withdrawal, paid for no-till services to sow maize on their fields. The drop-off farmers are those who stopped engaging in the subsidy package agreement or ceased hiring no-till planters. The CA area includes all land sown with the no-till planter at the time of the survey in 2017 (CA farmers), while the drop-off area includes all the land that discontinued the sowing service.

The data generated from these different surveys was used as background information to design and calibrate the decision model core with the RPG. Other data was then used to validate and/or to generalize the results of the RPG.

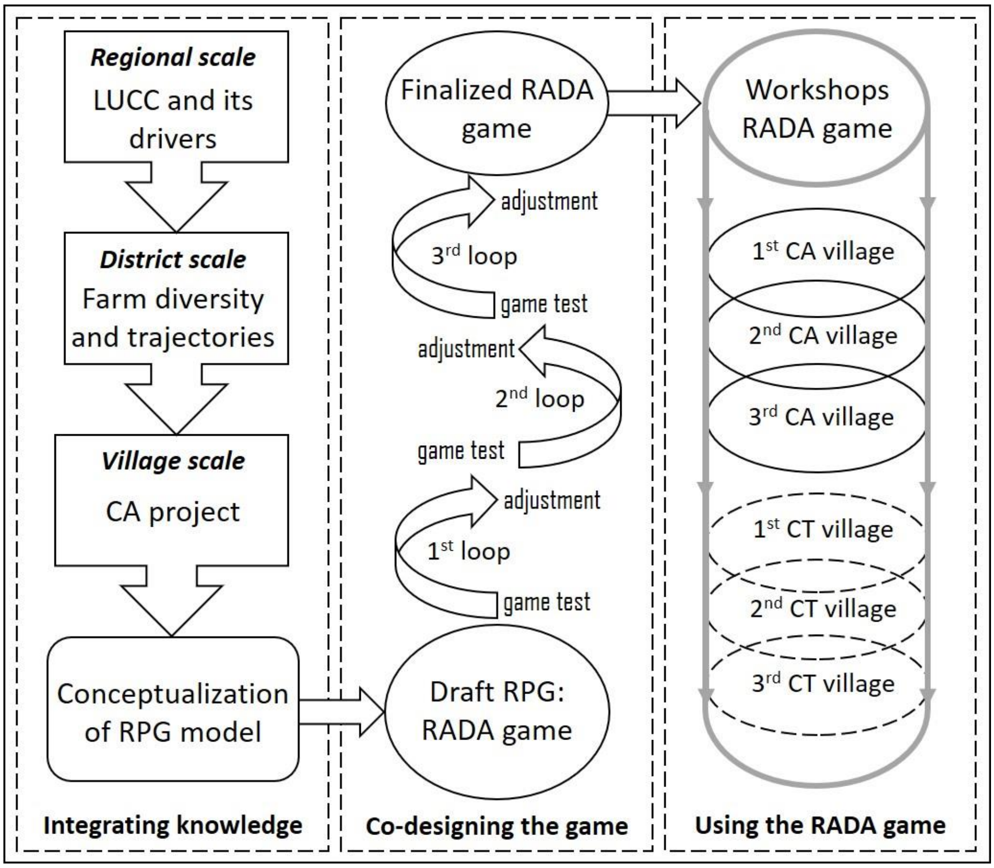


Figure 22: Graphic representation of the methodological framework

4.2.3 Co-designing and using the RADA game: Resilient Agriculture through co-design of Agroecology pathways

The co-design process took place in two steps: (i) expert seminar and prototyping; and (ii) testing and refining the game with the farmers. The expert team reviewed the data generated from the studies introduced in the previous section and developed a conceptual model of land use changes centered on farmers' decision making and changes in local institutions over the past decades. A prototype of the game was then designed by considering its representative reality and playability. The game testing and refining process was done through successive learning loops in three villages (Figure 22) with eight farmers per village from four different farm types of farm typology (Appendix 11 and Kong, n.d.). The three co-design sessions led to refining the rules and parameters, elicitation and calibration and to simplify the game to be playable by the local farmers. The team also gradually refined the roles and procedures for facilitation and monitoring. A full sequence of the RADA game is shown in Figure 23, which contains 6 rounds and 87 steps in total. Each round corresponds to a specific period marked by the introduction of a new crop or technique that dramatically influenced LUCC, such as the introduction of hybrid maize in 2006, CA techniques in 2010 or orchards in 2016. A round consists of five steps: 1) round introduction; 2) game play; 3) risk management; 4) result assessment; and 5) round debriefing. Details of the co-design process are provided in Appendix 14.

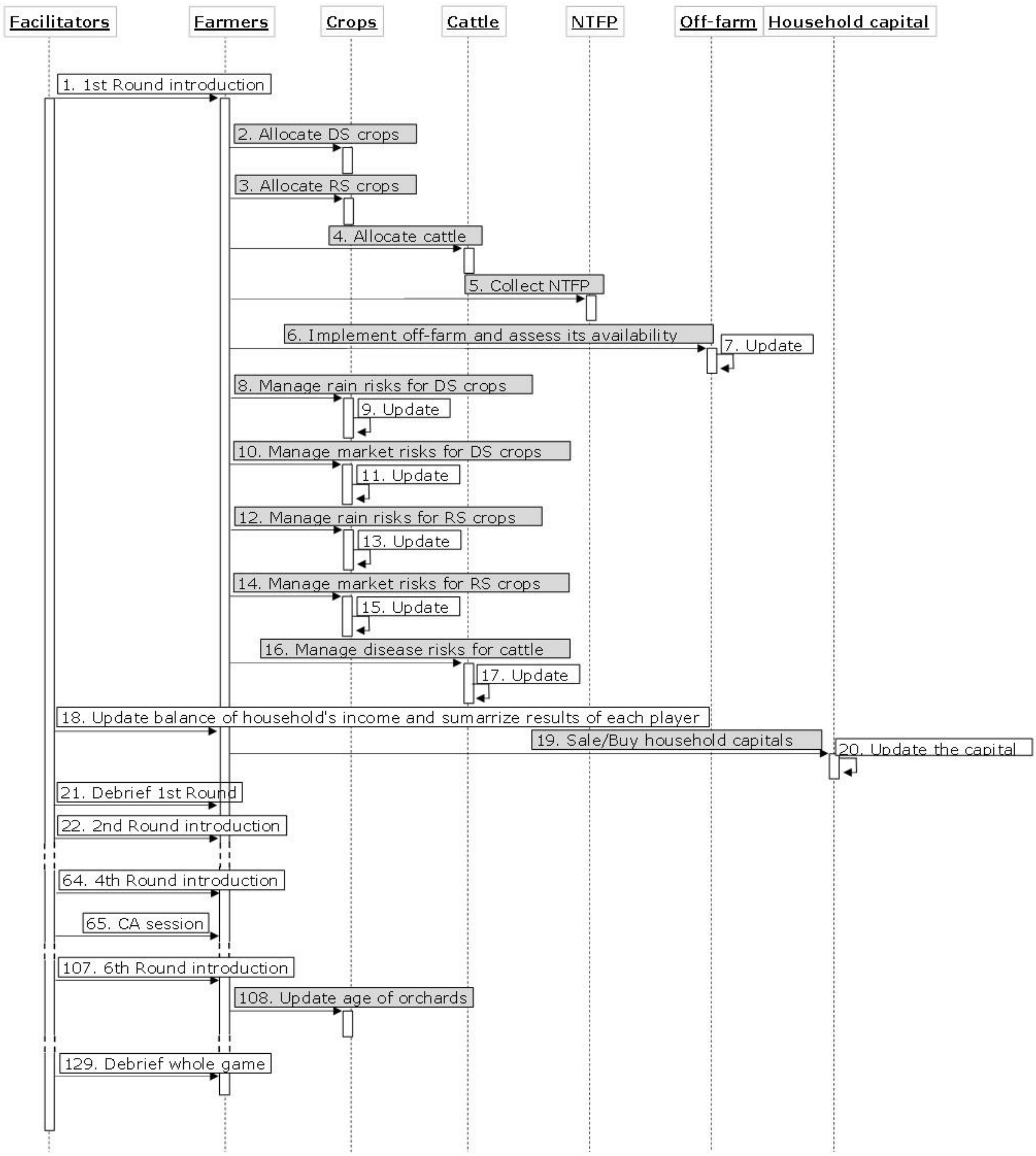


Figure 23: Unified Modeling Language sequence diagram of the RADA game

The RADA game was subsequently used to play systematically in six villages of Rotonak Mondol District in January 2018, all from the same village type, the Upland-Diversified Village (Appendix 11). Three of them were target villages of the CA project while, in the absence of project intervention, the three other villages had only practiced conventional tillage (CT) on upland crops as opposed to CA. In each village, we used the same spatial organization (Figure 25), allocation of initial resources to each player (Table 10), and rules and parameters (Appendix 13). Some rules and parameters are different from one round to another adapting to reality. The introduction of Round 4 included the CA techniques by using video clips and photos containing experiences and testimonies to promote the practice especially in CT (i.e. non-CA) villages. Generally, the players aim at optimizing farm income with the available resources and with the lowest risk possible. The process of farmer's decision-making in the game is illustrated in the Unified Modeling Language (UML) graph in Figure 24.

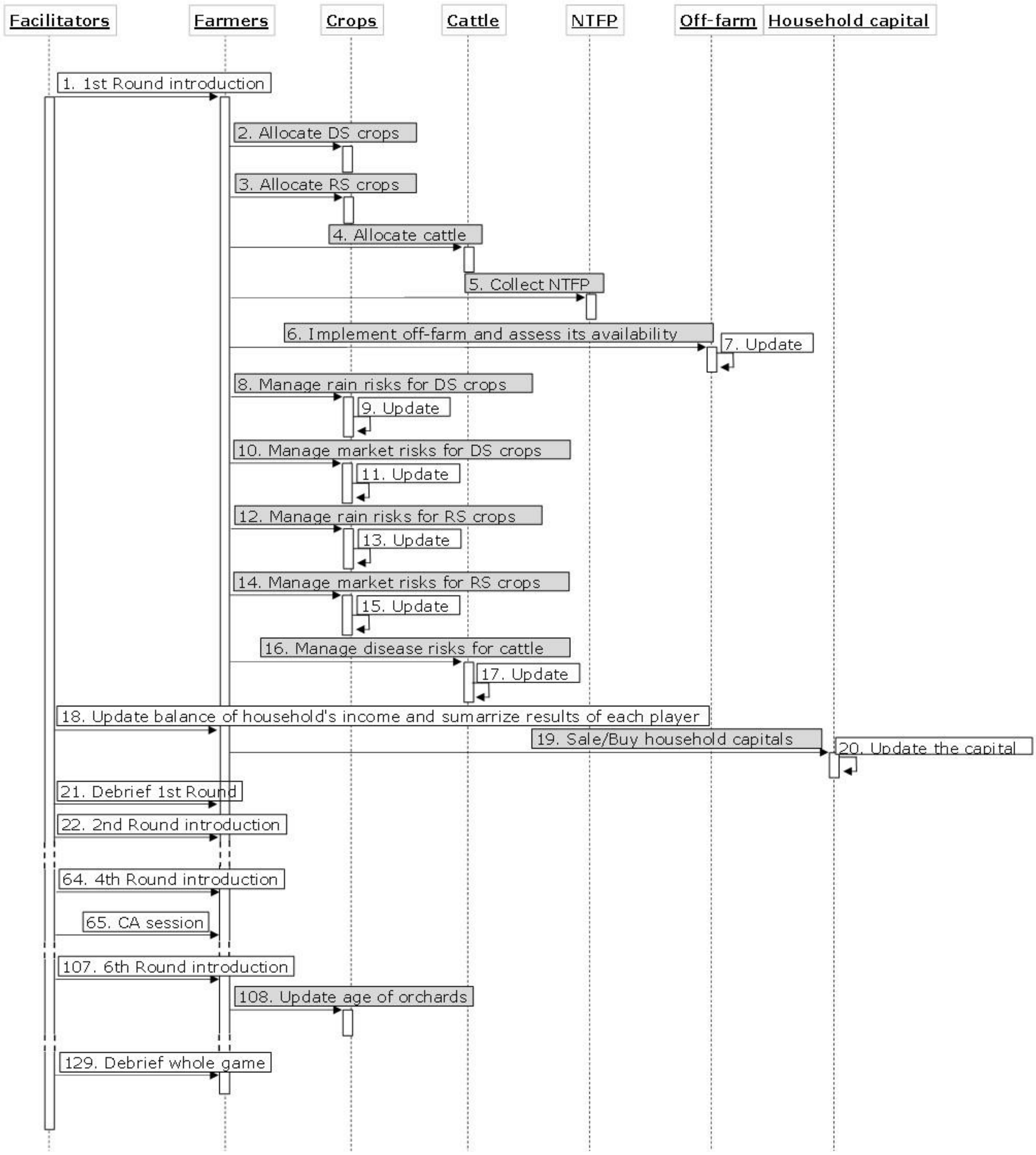


Figure 23Figure 24: The detail use of the RADA game (also described in Appendix 14)

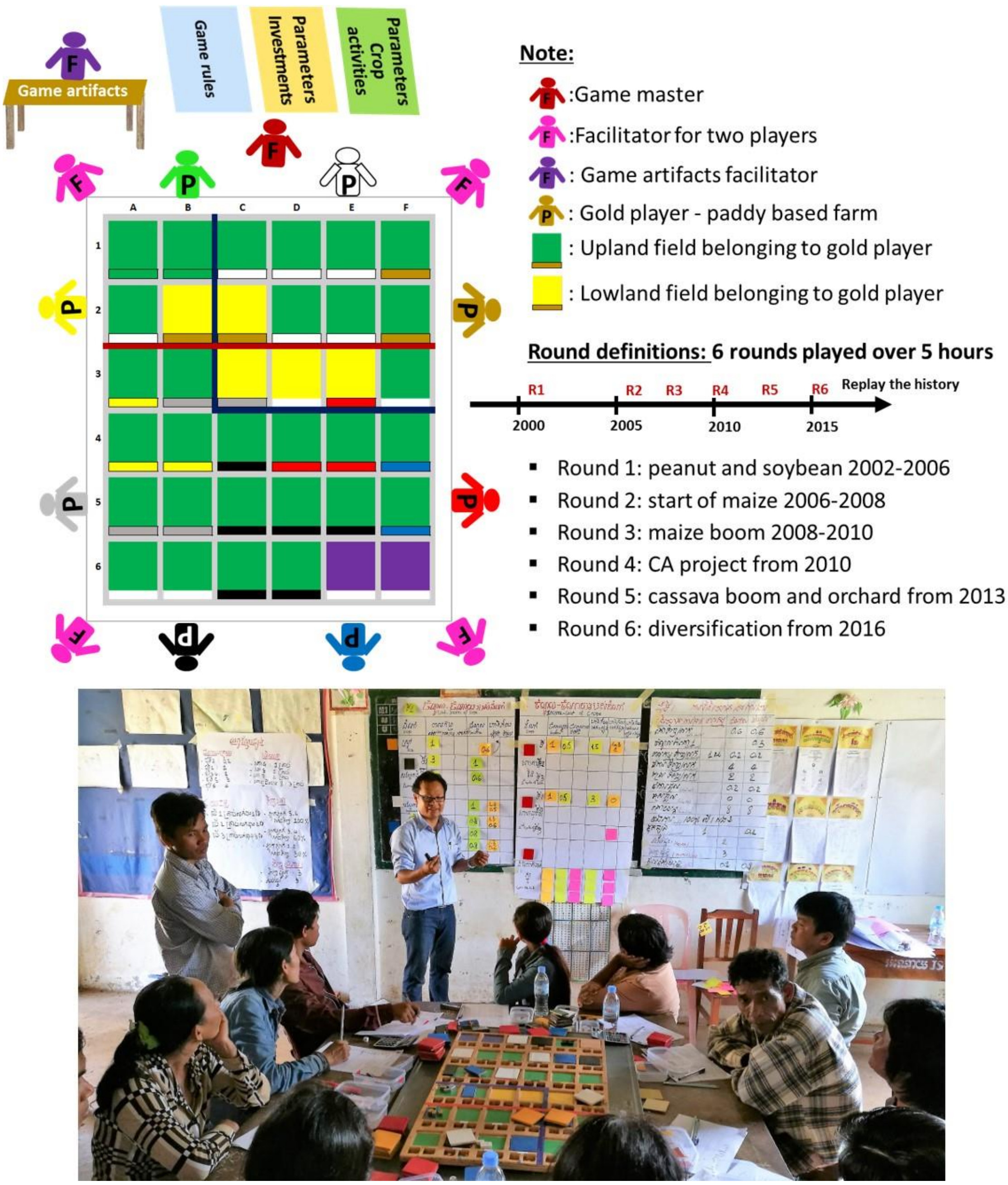


Figure 25: Spatial organization of the room and round definition

Table 10: Initial conditions of the RADA game - resources allocated to each farm type

Farm types	Color	Upland†	Lowland†	Farm labor		
				Person‡	Button§	Cattle
Upland crop-based large farm	black & white	6	0	4	24	4
Upland crop-based smallholder farm	red & yellow	3	0	3	18	0
Paddy based farm	gold & silver	2	2	4	24	4
Off-farm income dominated farm	green & blue	2	0	2	12	0

Note:

† number of cells in the board game

‡ number of active family labors

§ one button = 2 man-months labor force

4.2.4 Data collection and analysis

The facilitators recorded the data of their respective players in two forms, one at the farm level concerning economic results, resource changes and investment activities, and another at the plot level concerning land uses, cropping practices and risk management. The game master took notes on: (i) general observations during the play on important changes, interactions, and discussions between the players; (ii) the debrief of each round on the reasons of changes in land use, crop choice, farm resources, innovative techniques and farming constraints; and (iii) the overall game debrief of the RPG session. The collective debriefing included feedback on the game, i.e. how close it is to the reality, how and why it is useful; and the main lessons learnt by both players and facilitators about impacts of boom-bust cycles, perception on soil conservation practices…etc. Each gaming session was voice and video recorded. These records were used to clarify discussion content when necessary as many actions happened in parallel during the game and complemented the notes taken by the game master. An individual survey was conducted by the game master with each player in order to understand the logic behind the decisions made during the game, especially the reasons for adopting CA, dropping-off CA and continued CA in relation to their farm type and the adoption period (i.e. with or without subsidies).

A template was created under Microsoft Excel to systematically key in the data recorded in the paper forms. We then computed a number of economic and environmental indicators at both farm and village scales. The indicators are described in Table 11. The values of the indicators were also extrapolated for Round 7 so that the delayed income from mature orchards planted in Round 6 could be accounted for in the results. Otherwise the orchards would have only appeared as large investments without return during the time period of the game. The information collected through the voice and video records, the written notes, and the follow-up survey were systematically categorized to compute the indicator values, to explain the perception on the CA techniques and farming perspectives and to generalize a model of the decision-making process from the six RPG sessions, considered as collective experiments.

Table 11: List of indicators used to monitor the game

Indicators	Definitions
Capital accumulation (million KHR)	Total value of investments (land, cattle, orchard installation…etc.) and assets for agriculture (i.e. power tiller) and domestic (i.e. motorbike) use from all households in the village.
Shannon diversity index of land use	Proportion of area of land use type i relative to the total area of land use (pi) in the village is calculated, and then multiplied by the natural logarithm of this proportion (lnpi). The resulting product is summed across cropping systems and multiplied by -1.
Mechanization service cost (million KHR/ha)	Average service cost per hectare and per year for agricultural machineries in the village.
Pesticides use (l-kg/ha)	Average amount of pesticides (herbicides, insecticides, and fungicides) per hectare (quantity of commercial product).
Agricultural productivity (million KHR/ha)	Total gross value added of crop and cattle divided by the total agricultural land used both inside and outside the village.
Labor productivity (million KHR/person)	Total gross value added of crop and cattle dividing by the total family labor in the village.
Return on investment (%)	Proportion of total gross value added of crop by the total production cost in the village.
Soil fertility depletion (% of initial soil carbon content)	Sum of average score of soil organic matter depletion for each cell/plot within the village from Round 1 to 7. The depletion score is assessed by expert's knowledge based on the cropping systems, i.e. dry season maize followed by rainy season maize: -25% (two plows); cassava: -30% (two plows and one ridge); improved pasture and rotational grazing: +15%
Rain and market vulnerability	Sum of multiplication between probability of loss and the amount of loss related to rain and market risks for each practiced cropping system per hectare and per year.
Total cattle (head)	Total number of cattle in the village.

4.3 Results

4.3.1 Market opportunities and economic return as main drivers of farmers' decisions

In the early 2000s, semi-subsistent farming prevailed with limited access to markets and a poor road network. Most farms were growing rice and additional cash crops such as peanut, soybean, sesame, and mungbean. The choice among these crops was conditioned by seed availability depending on the village of origin, of migrants, technical knowledge and a local collector to buy the harvest. Farmers' decisions were mainly driven by the need to produce sufficient rice to eat while generating income from the cash crops to continue forest clearance. The other determinants were the availability of family labor or capital to hire daily workers for land clearance that defined the agricultural land available to each household after a few years. Farm resources (i.e. labor, land and capital) were therefore closely interlinked with the capacity to clear forests during that first period. The first round reminded the players of the importance of their 'initial conditions' as recent migrants to their current status, i.e. farm type (Kong, n.d.), about two decades earlier.

The farming systems became fully commercial from mid the 2000s, with the introduction of hybrid maize and agrochemical inputs in particular herbicides associated with improved market access and road infrastructure. The economic productivity of land, which is a function of obtainable yield, production costs and farm gate prices, was the key factor in deciding which crops to cultivate. The farmers quickly cropped all their uplands with two cycles of maize per year as maize provided the highest economic return, whereas rice could be purchased from the market. In the second round of the game, farmers expanded maize areas to their entire upland surfaces and also to some rented lands in neighboring villages. Maize reached more than 70% of cultivated areas in the Round 3 (Figure 26 and Table 12) as in reality (Kong et al., 2019). The game confirmed that the farm gate price of maize was a dominant factor since the newly reclaimed lands were highly productive, rainfall was well distributed, and production costs were low.

However, these three elements of economic productivity were equally important in the early 2010s (i.e. Round 4 in the game) when the yield of maize was declining and production costs were increasing due to (i) soil fertility depletion (intensive tillage and mono-cropping without organic matter input), (ii) increasing agrochemical inputs (i.e. chemical fertilizers), and (iii) mechanization to offset labor scarcity due to young people fleeing to the cities (Kong et al., 2019). In Round 5, farmers massively shifted from maize to cassava for its higher economic productivity. From 20 to 61% of the agricultural area was converted to cassava depending on the villages, representing 40% on average (Figure 26 and Table 12). Meanwhile, price fluctuations and rainfall variations became increasingly important factors in the decision. In the game, to cope with these risks, most resource-rich farmers (i.e. Upland crop-based large farm) converted their land to orchards with longan and mango trees while the others tried to diversify with livestock, vegetables and off-farm activities. The high economic return of mango plantations led to a rapid land use conversion of 13 to 31% of the cultivated area (Figure 26 and Table 12). In 2015 for instance, a 5-year-old mango plantation could be rented at 3000$/year/ha or provide 10,000$/year/ha gross income, which is 5-10 times higher than cassava or maize, respectively. High expectations on economic return encouraged resource-poor farmers to invest in such high-risk business, for which most had to take more loans while not knowing where and to whom to sell the mangos. In addition, the game revealed that investment in tree crops is part of their long-term strategy to withdraw from agriculture, by orienting their children to non-farm activities through higher education. In addition, tree crops provide regular income with less labor input, a key limiting factor for elder farmers.

In summary, full market access dramatically changed farmers' perspectives from rice sufficiency to agribusiness. High economic returns from hybrid maize ushered in a prosperous period from the mid-2000s. Every single farmer remembers it as their highest ever income from the upland farming leading to rapid improvement of their living standards through an accumulation of capital and assets (i.e. housing, power-tiller, motorbike). The myth of getting rich from farming emerged at that time and spread to other upland regions in Cambodia. The game results confirm these dramatic changes with farm income increasing 5 times for upland farmers - versus 2.5 times only for those in paddy-based farm type - in Round 2, and 10 times in Round 3 (Table 13). The elements and their relation to farmers' decision-making strategies are illustrated in Figure 27.

Figure 26: Results on board game from one of the six villages

Table 12: Average area (%) of crops grown per villages in the game

Round	1	2	3	4	5	6	7
Cassava	0	0	0	0	39	9	7
Chili	2	0	0	0	0	0	0
Cover crop	0	0	0	35	7	12	13
Longan	0	0	0	0	2	4	4
Maize	0	71	68	47	17	17	17
Mango	0	0	0	0	20	37	38
Mungbean	27	14	19	10	3	5	5
Paddy rice	14	7	6	6	5	4	4
Pasture	0	0	0	1	6	9	10
Peanut	20	2	1	0	0	0	0
Sesame	14	4	4	0	0	0	0
Soybean	18	2	1	0	0	0	0
Upland rice	6	0	1	0	0	0	0
Vegetables	0	0	0	0	1	2	2
Total cultivated land (%)†	32	79	87	99	97	104	101

† In some cases, the total is higher than 100% because the villagers rent in land outside of the village.

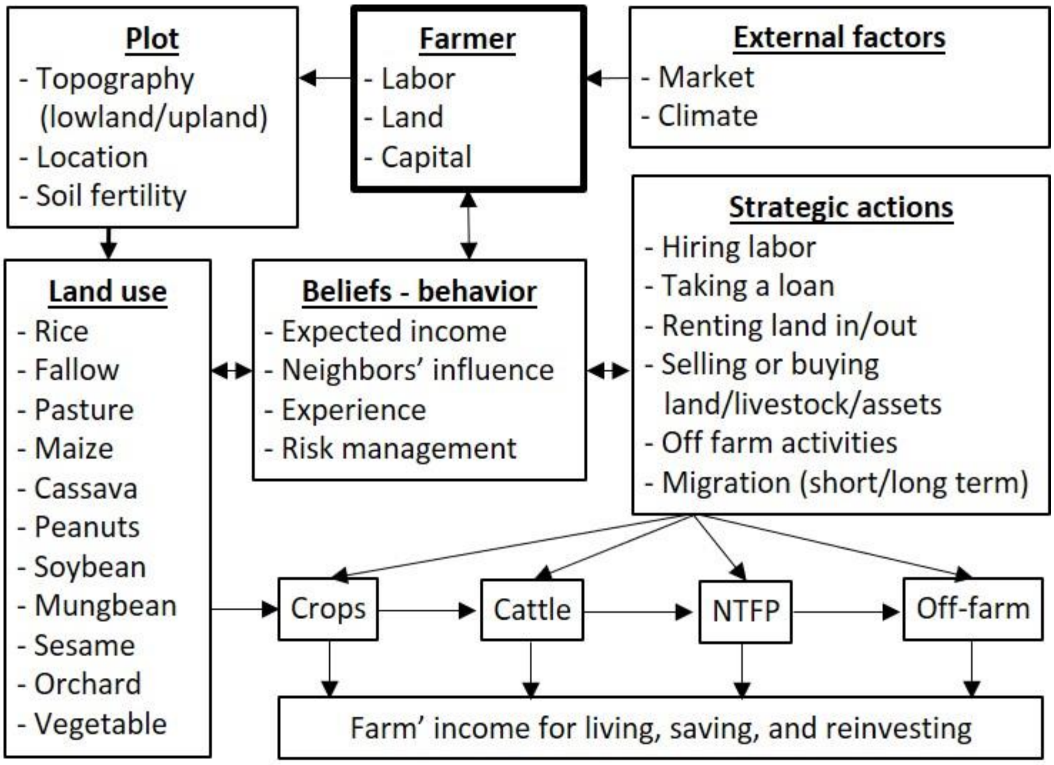


Figure 27: Diagram describing the farmer's decision-making process

4.3.2 Opportunistic conversion to new cash crops in the face of land degradation

After a few years of maize monocropping, yields started decreasing, although the associated economic loss was temporarily compensated by the increasing farm gate price of maize allowing farmers to maintain their revenues at a decent level. Farmers were not much concerned as long as maize provided higher economic returns than any alternative crop or farm activity. They attributed the yield decline to seasonal climatic accidents. They clearly perceived soil fertility depletion and yield decline but did not react to it since it was not affecting their income. However, during the game debriefing, the majority of farmers admitted that they had no choice, and were obliged to apply chemical fertilizers when the yield went down to a critical level. Chemical fertilizers, like maize seeds and herbicides, were widely promoted by agribusiness companies that convinced the farmers it was their only option to sustain the yield.

During the game, very few players chose environmental benefits over economic ones by diversifying the crops through rotational and sequenced cropping with pulse crops or improved pasture. Those who did explained that they played it safe because they already knew what would happen in the game from their own experience if they were to stick to maize monocropping beyond Round 3. They mobilized their experience in the game but freely admitted that they would fall into the same trap if a similar situation would present itself again.

Indeed, problems accumulated at the end of the 2000s. They were (i) technical, i.e. yield losses, pest damage, agrochemical dependence, (ii) economic, i.e. increasing production costs and indebtedness, price fluctuations, and (iii) environmental, i.e. soil erosion and fertility depletion, increasing rainfall variability (Table 13). However, an alternative to maize appeared in the form of cassava which was booming at the same time in other provinces (Mahanty and Milne, 2016). Cassava appeared as the last annual upland crop that could produce accepted yields on depleted soils due to the occurrence and synergistic effects of arbuscular mycorrhizal fungi (Howeler et al., 1982), and plant growth-promoting rhizobacteria (Arruda et al., 2013) along with its nutrients' recycling abilities. In addition, conventional practices of cassava cultivation, involving deep plowing and ridging, contributed to soil erosion by run-off and oxidation of soil organic matter while generating a high uptake and exportation of nutrients by the cassava tubers, mainly potassium.

The cumulative effect of conventional tillage systems on soil fertility depletion was simulated by introducing a 'soil capital' parameter that would be depleted over successive years of tillage and monocropping and would be replenished by no-till practices, mulch and cover crops as well as rotations with legume crops. Despite information provided to the players concerning the negative effects of conventional practices, their decisions led to soil fertility depletion down to 43% of the initial soil capital in Round 5 (Table 13). While many farmers adopted soil conservation practices as an option to sustain their yield and income (see next section) the game showed that their preferred action, in the case of decreasing crop profitability, was to switch to another commodity. This explanation was systematically provided by participants to justify their massive conversion to cassava in Round 5 and orchards in Round

6. Nevertheless, lessons from past experiences led some players, usually the small-medium land farmers, to diversify agricultural activities through cattle raising and off-farm activities in Round 5 (Figure 28 and Table 13) as a coping mechanism to buffer economic risks.

Farmers have gradually increased the amount of risk they were ready to bear by adding the risks of market failure and price fluctuation to prevailing weather variability. At the initial stage of adoption, farmers/players often simplified their economic calculations by discounting the risks. They somehow postponed the time they would have to deal with gradual depletion of soil fertility and unpredictable extreme events (both economic and environmental). During the game, they had to deal with these risks but they were always hoping for another, more productive alternative 'boom crop' to pop-up to support further economic development as happened in the past with maize, cassava and mango. Otherwise, the alternative income sources for resource-poor households would involve migration, in search of off-farm jobs in the garment industry or in neighboring Thailand.

Table 13: Impact indicators of farmer's decision on land uses and practices

Round	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Capital accumulation (million KHR)	1	7	75	127	183	246	246
Shannon diversity index of land use	1.91	1.64	1.64	1.27	1.83	1.84	1.79
Mechanization service cost (million KHR/ha)	0.04	0.58	0.58	0.53	0.77	0.99	0.98
Pesticides use (l-kg/ha)	0.00	3.33	5.45	4.57	4.33	11.54	12.26
Crop land use productivity (million KHR/ha)	0.98	3.45	2.55	2.37	2.81	4.90	4.98
Crop labor productivity (million KHR/person)	0.79	4.30	3.28	5.70	6.58	15.41	16.10
Return on investment (%)	328	229	144	153	140	112	111
Land degradation accumulation (%)	-1	-16	-30	-27	-43	-42	-41
Rain and market vulnerability	0.03	0.10	0.23	0.19	0.15	0.21	0.21
Total cattle (head)	16	24	43	68	69	73	73

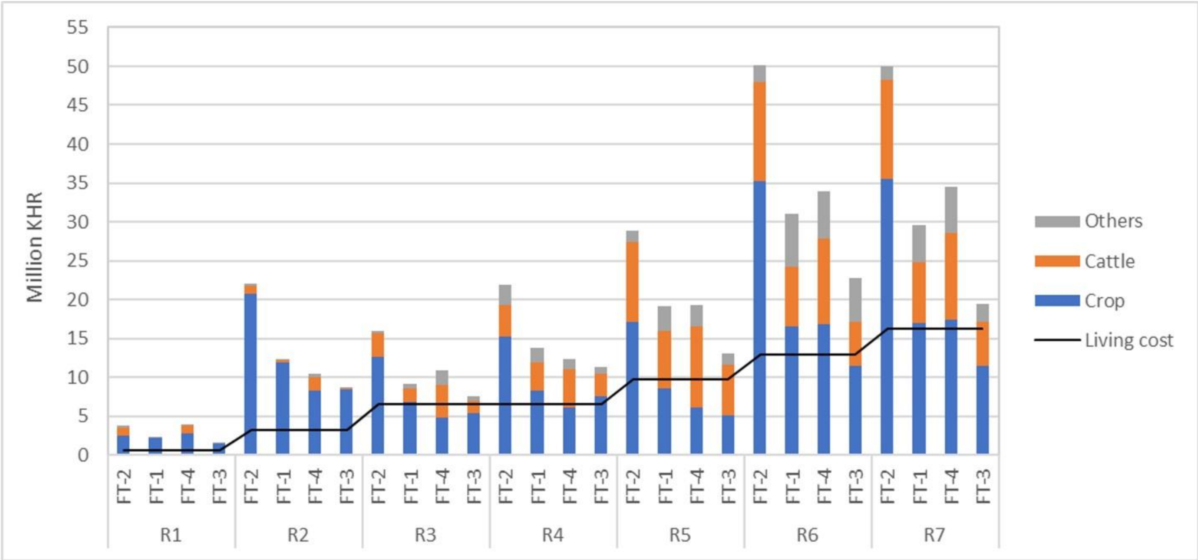


Figure 28: Composition of farm income for the four farm types in Rotonak Mondol

4.3.3 Perceptions and impacts of the CA project

Alternative cropping practices were introduced by the CA project together with different intervention mechanisms during the two periods mentioned, i.e. with subsidy (2010-2012) and without subsidy (2013-2017). The first period corresponded to the tip of the maize boom curve, when farmer adopted massively the high-input, monocropping system. During the second period, farmers faced declining yields due to soil fertility depletion as alternatives to maize emerged in the form of cassava and fruit trees. Therefore, both the contexts of intervention and the intervention mechanisms differed during those two periods.

During the first period, the most important reasons for the farmers to experiment CA were (i) curiosity, (ii) the interest free credit and yield insurance included in the package, and (iii) labor saving using the no-till planter service (Figure 29.1). The curiosity factor was the highest among the upland crop-based large farms who were anxious to learn about the risk of insect damage at the early stage, if CA techniques would improve maize yield, and if soil fertility could be maintained. In contrast, the subsidy package and labor savings were dominantly reported among the upland crop-based smallholder farms, off-farm based farms, and paddy-based farms; these were high incentives to CA adoption as they could invest the saved labor in other activities. Some large upland farms also tried the CA package on some of their land to reinvest the labor saved on CA fields through the interventions of CA technicians in other maize fields managed under conventional tillage.

After the end of the subsidy period, the main reason to try CA became the quality of sowing, seed savings, and yield increases (Figure 29.1). These three factors were related to the use of the no-till planter as it allowed saving seeds as compared to other planters or manual sowing, provided more regular sowing density and seedling emergence and therefore increasing yield. There was no significant difference between farm types in terms of CA adoption during the second period. The increasing number of CA households and areas is attributable to the flexibility provided by the project on all components of crop management other than the CA sowing service. The project charges farmers for the sowing service ($35/ha) and provides free technical advice. Farmers thus perceived CA practices as simpler than during the first period when the package was coming with a cover crop that they could not harvest as it was used as mulch for direct sowing of the main crop. During the second period CA farmers could harvest two crops per year in some cases (mungbean – maize, maize – mungbean mainly) and till the soil. Yet, some continued no-till practices, or reduced the number of plowing for example to broadcast mungbean or sesame early in the wet season and do direct sowing of maize in the mulch of former crops.

The results obtained from the surveys were confirmed by the RADA game when we simulated the introduction of CA practices in Round 4. In addition to soil fertility management, the higher income and lower labor requirements provided by the mechanized sowing on no-tilled fields equally aroused farmers' interest. However, the CA adoption rate in the game, up to 80% in both CA and non-CA villages (Figure 30) was much higher than what happened in reality. During the debriefing sessions, farmers admitted that they were playing the game with their current experience of depleted soils and decreasing yields while they were less concerned by this at the time of the CA packages when the yields were still high.

The reasons for abandoning CA during the subsidy period were that farmers believed they would get the same or lower yield, would incur higher production costs in particular on chemical fertilizers, and high weed pressure, leading to lower economic returns from CA as compared to CT (Figure 29.3). The ban imposed by the project on atrazine and paraquat herbicides, commonly used in CT, made weed control less efficient and consequently lowered yields in already high weed pressure fields. The application of chemical fertilizers to rebalance soil nutrients and boost yields was not fully responsive since the rainfall distribution became increasingly erratic. Some farmers applied lower doses to save it for CT or paddy fields. In addition, large upland farmers complained about the technical complexity of the CA package which required many operations, strict timing and field care. On the other hand, the small upland farmers who dropped CA explained their decision by their small land area which they needed to harvest twice a year to sustain their income and have a higher cash flow.

After subsidy withdrawal, farmers dropped-off CA exclusively to shift to cassava and orchards (Figure 29.3) particularly after 2015, which led to a sharp decrease in the number of CA farmers both in the game and in reality, without noticeable differences between farm types (Figure 21 and Figure 29.3). This massive shift was justified by the higher economic productivity of cassava and orchards as compared to maize. There was no CA alternative readily available for cassava since the project did not have a no-till planter available for cassava, and CA for orchards was outside the project's scope. Limited farmer access to the no-till planter was also a cause of CA drop-off during that second period. The CA project had only two planters, and the demand for no-till sowing services was not found in additional villages to be economically attractive for a private contractor to engage in this new business. In addition, availability of no-till planters and their purchase cost were among the main constraints in the dissemination of these tools. Nevertheless, some farmers continued CA during and after the subsidy period thanks to better sowing quality, seed and labor savings and the technical advice provided by the Project (Figure 29.2). In 2017, due to low productivity and profitability of cassava in 2016, the maize area under no-till sowing increased to reach 272 ha representing 94 households. This result emphasized the quick reactivity of the farmers and the need for options (new agricultural implements, availability of pulse crop and/or cover crop seeds) to foster the dissemination and adaptation of new practices. In the game, CA farmers continued CA on about 50% of the cropped area (Figure 30). This result is consistent with a survey of CA farmers in 2014 which found that they practiced CA on more than 50% of their farmland. In addition, CA farmers had more diversified crops with a smaller share of their land shifting to orchards than in the non-CA villagers.

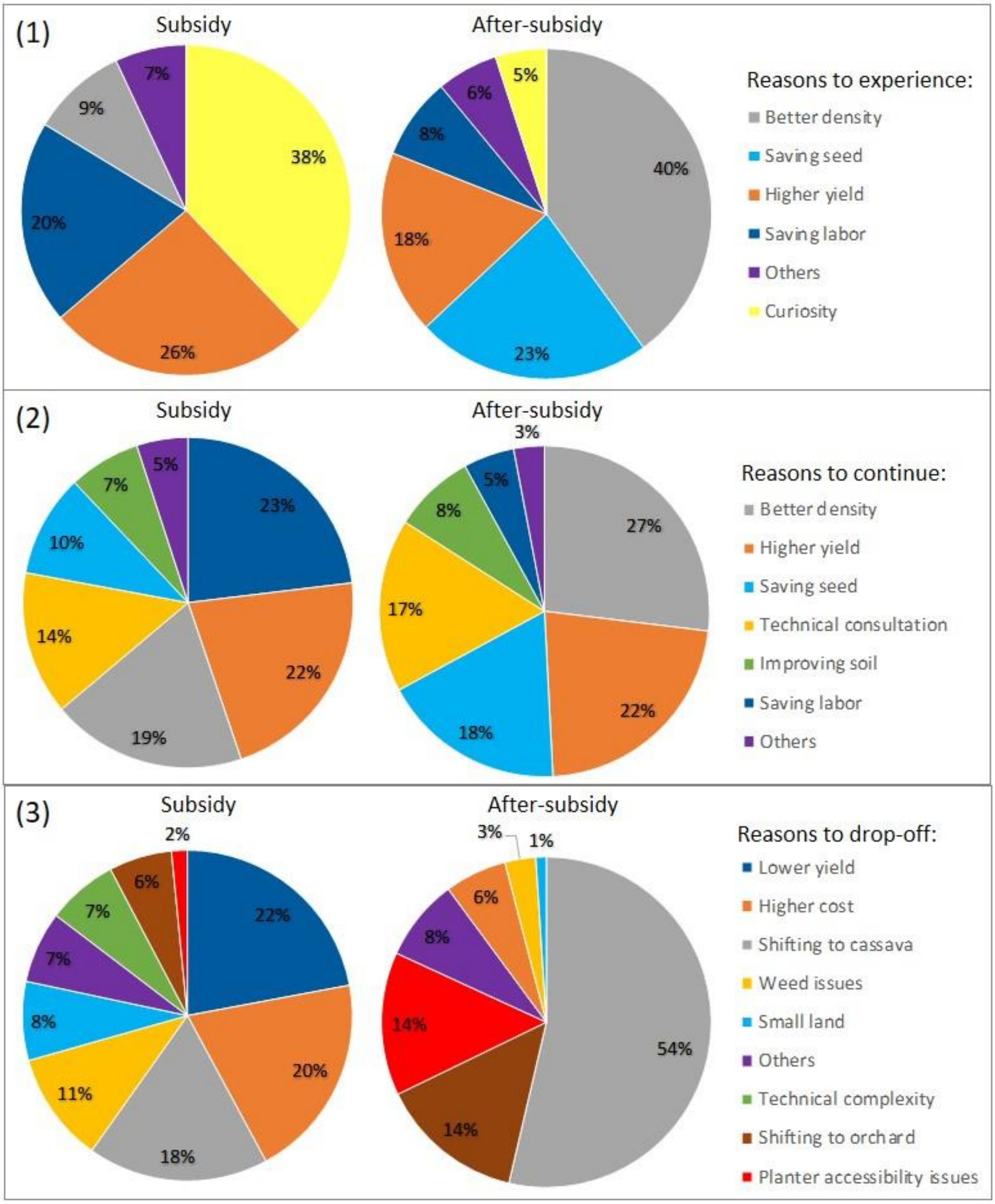


Figure 29: Reasons to experiment CA and drop-off during and after the CA subsidy period

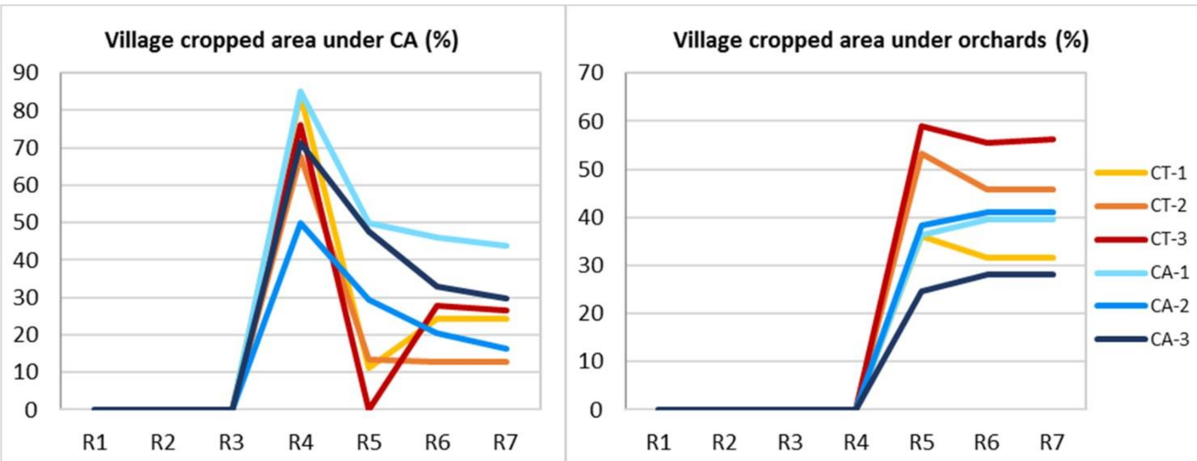


Figure 30: Village cropped area under CA (%) and orchards (%) during the game

4.4 Discussion

4.4.1 Using gaming approaches in investigating land use change

The RADA game convincingly simulated land use changes in the study district over the past decades. It reproduced the situations faced by the players at the key times of decision and negotiation along their land use trajectories. At the village level, we could identify the minimum set of parameters that captured the main drivers of land use change, their causal relations and their relative strength during the successive periods (Appendix 13). This was the result of successive learning loops using the game to elicit local knowledge and to validate our understanding of the decision-making process obtained from individual interviews and focus group discussions (Perrotton et al., 2017; Speelman et al., 2014). Despite the limited numbers of players who took part in the co-design phase (# 24) and the implementation phase (#48) of the game, we are confident that the game captured the main features and trends of the upland villages in the study area (Kong et al., 2019). We could not compare the outputs of the game with those of the surveys through a formal validation procedure relying on statistical analysis because the number of villages was too small. Instead, we did a participatory validation of the game design with participants at the implementation phase during the debriefing sessions. The participants confirmed that the game adequately captured the recent changes in land use and the diversity of farming systems. They confirmed that the decisions they took in reality had the same causal relations as the ones they played in the game. At the farm level, we could investigate the conjunction of factors, related to the local context (i.e. innovative practices, commodity prices), the farm conditions (i.e. land, labor, capital), the individual knowledge, perception and behavior (i.e. vanguards, risk avoiders, imitators) that resulted in the decisions made at a particular time and place.

The only important difference between what happened in the game as compared to reality was due to the time gap between the periods that the game simulates and the current situation. Participants re-play their past decisions with their current mindset and experience. They tend to play their present, not their past or future in the game (i.e. cattle, improved pasture, and vegetables). They recognize that everything that has happened since then did influence their decisions during the game. For example, their perception about the risk of maize yield collapse is very different today as compared to the mid-2000s. At that time, they thought they would grow maize forever with the same yields but now they know that the collapse can happen as they lived it. Therefore, they are more eager to take action on sustainable land management today than in the past, when they arrived in the pioneer front as young migrants. In an attempt to avoid this time lag effect, Ornetsmüller et al., (2018) sampled villages that were considered at the successive stages of the land use trajectory at the time of the gaming sessions. Remoteness and accessibility issues of some villages allowed substituting distance for time. However, such sampling design was not possible in the case of Cambodia as all villages are easily accessible. It was not possible to find villages today in which agriculture resembled that of the last decade.

4.4.2 Revisiting agricultural innovation systems through participatory simulations

4.4.2.1 Opportunity windows

The CA project intervened during the expansion phase of the maize boom (Kong et al., 2019). Gaming sessions confirmed that farmers did not perceive soil fertility issues at this time and were not ready to take action. If the game would have been played at that time, we could imagine that this would have been much more powerful an issue than it did years later, once the farmers underwent all stages of the maize boom, including the bust phase. We used the concept of opportunity windows (Castella et al., 2012) to draw practical lessons from these results. We identified periods in local land use trajectories when the introduction of innovative systems is more susceptible to failure. This was especially the case at the beginning of the boom crop expansion, when the new crop allowed a big jump in economic returns and fertility depletion was not visible. The crop spread rapidly and easily with the support of the agribusiness companies, and farmers largely ignored the messages promoting alternative cropping practices. This phenomenon was described in different agricultural contexts and with different crops (Cramb et al., 2017; Hall, 2011; Mahanty and Milne, 2016). Actually, interventions should target the periods that precede the booms to prevent its disastrous consequences, or in the aftermath of the boom to engage with communities in landscape restoration. The gaming approach has shown its relevance in rapidly identifying these windows of opportunity with local communities to identify the most favorable time for intervention according to place (Ornetsmüller et al., 2018).

4.4.2.2 Converting to CA

In our case study site, the CA project incentivized the adoption of a full technical package including cover crop, no-till planter, free credit and yield insurance to convince farmers to test the new practices at the most difficult stages of the land use trajectory. Some farmers somehow took advantage of the project package to their short-term benefit. They took the subsidies or saved labor thanks to the direct time investment of a project technician in their demonstration fields. However, farmers perceived CA as an innovative package that was technically complex and against their logic of crop management simplification with herbicides, fertilizers and mechanization where ‘cropping is plowing’. The large quantity of biomass produced by the cover crop to boost soil fertility and improve yields did not provide the short-term economic rewards expected by early adopters of the first period. Farmers, like some of the project’s young technicians, were still conceiving CA techniques in a logic of monocropping and did not yet consider the need for diversified cropping systems and complex landscape mosaics. In addition, the agribusiness companies were promoting only one crop at a time (i.e. maize) and thus the market for pulse crops became almost inexistent. Landscape restoration requires methods, tools, and expertise that were not available at that time to “redesign” the whole socio-ecological system. Finally, the project interventions failed to create the critical mass of CA farmers that would have raised the interest of private contractors to engage in a no-till sowing service. Additional connections need to be developed between service providers and local entrepreneurs providing agricultural machinery services to farmers.

4.4.2.3 Transitioning to CA

During the second period (no subsidy), many farmers switched to cassava as an alternative to maize. Only a few of them were still interested in the CA package, as it was adapted to maize only. Their main interest was to continue accumulating capital quickly with boom crops as they did with maize during the previous period, then to shift again to another commodity even with high risks and investment when profitability would decline. Cattle and off-farm activities were considered as safety nets when investing in risky boom crops such as cassava first and then orchards. Within such a new context, as simulated during Round 5 of the game, the underlying logic of the CA package was no longer relevant. The project changed from a logic of conversion from one cropping system to a completely different one (CA) proposed as a package, to a logic of transition considered as a stepwise process that would gradually include elements of CA within the existing cropping systems. This transition logic was combined with an objective of diversification. During the second period, the project provided elements of innovation for all land use types (not focusing on maize only), for example orchards, pasture, vegetables, cattle, cassava…, in an attempt to improve cropping systems within a larger perspective of sustainable landscape management and integration of all actors of the innovation system (including agribusinesses, NGOs, etc.) in the local development process. Impact was then measured in terms of the changes induced in individual behaviors, interactions among stakeholders, perceptions on soil fertility, management of wild fires, understanding of crop diversification (even if diversification was slow…), and no longer in a simple accounting of the number of project beneficiaries. The game thus showed its capacity to address not only technical aspects but also social aspects of the CA innovations, collective processes and eventually market linkages with operators involved in different value chains.

4.4.3 Making agriculture great again in Rotonak Mondul

4.4.3.1 Social organizations

The gaming approach pointed out a number of technical constraints to larger adoption of sustainable cropping systems such as the availability of planters for direct sowing in mulch or CA alternatives for cassava-based cropping systems. So far, the CA project manages all equipment and services as the private contractors do not see the short-term economic value of such investments. Support is needed to catalyze the growth of this demand and this market. In particular, there is a need to support service providers through a demand-creation process and to have increased access to affordable no-till planters. In addition, provision of financial support to service providers may be needed to support the transition from plow-based to no-till activities. This key turning point in the innovation process is reachable, but a number of organizational issues impede progress toward that stage. The game revealed some of these issues. We addressed them with participants during the debriefing sessions based on observations made of the imitative process and poor coordination among players during the game. At some stage, we were wondering whether the structure and process of the game itself were a constraint to interactions among farmers. However, participants confirmed that the observed individualistic behaviors were similar to their reality. They attributed these behaviors to the distance between farms, the large size of the villages preventing people from knowing each other, and the fact that people migrated from many different places and therefore did not share a common history at that place. In previous years, agriculture developed through pioneer front mechanisms (i.e. gradual forestland clearance by migrants – Rada Kong et al., 2019) and therefore did not require a strong social organization to expand. However, local farmers have reached land’s end and realize now that they have to reinvent a new agricultural paradigm. They have to shift from land rush and boom crop thinking to sustainable management. The game helped them realize that such movement would require dramatic changes in their social organization. Some players, especially in CA villages asked for support to develop farmer groups and cooperatives as a mechanism to boost the innovation process and bring CA practices to scale.

4.4.3.2 Social learning

The RADA game showed that analyzing the project in terms of CA adopters was misleading. Many farmers stopped practicing CA because they switched to a new boom crop (i.e. cassava) for which no CA package was available and not because they were not interested in applying CA. We could verify that they were well aware of the innovative practices, so the project managed to create a community of practice around the use of a CA implement (i.e. no-till planter) and advisory services. In addition, elements of social learning clearly emerged from the game when comparing the CA and CT villages. In the CT villages, several players were initially reluctant to adopt CA during Round 4 because they were afraid of the risk of fire that would be increased by the dead mulch in their CA plots. Their concerns were even greater with orchards since the investment is high. In CA villages, participants have more experience in fire control, for example they plow around the plots as firebreaks and teach their children the advantages of the mulch and not to burn it. Even though collective management was not reported, experiences were shared during the game and options for collective management were discussed and agreed upon. This institutional change was supported by the project but had never been attributed to it until we played the game. The game also revealed how poor farmers could follow their wealthier neighbors in the innovation process once the latter had demonstrated the potential benefits of a new practice or commodity. In a context of low social organization capacity (i.e. imitative behaviors, poor coordination), the gaming approach showed good potential for social learning.

4.4.3.3 Going to scale with the game

Beyond revealing changes in local institutions, the game may help enhance social learning. Reforming agriculture from a pioneer front to an agroecology realm requires major transformations in stakeholder interactions across agricultural landscapes and value chains. The RADA game showed its potential to raise awareness of land degradation by using early warning messages based on other indicators than yield decline. Indeed, crop yields decline when fertility is already depleted, and land restoration is more complex than at the initial stages of land degradation. In addition, the large agribusinesses prefer to specialize in one or a few industrial crops and therefore promote mono-cropping to facilitate their extension activities. With the boom of maize, cassava, and more recently fruit trees, some leguminous crops have almost disappeared from the market, which reduced the prevailing agrobiodiversity and prevented farmers and extension agents from introducing agroecological practices based on legume crops. Farmers who played the game were rapidly convinced of the value of these alternative practices and pointed to the many organizational constraints to large-scale adoption. This brought us to discuss with local people and district authorities a number of approaches to bring these results to scale. A first approach would consist of playing with multi-stakeholder groups involving representatives of the farmers, service providers, medium-manufacturers, local administration and agribusinesses to implement a pilot territorial approach beyond the pioneer front redesigning the landscape from field to market. A second, complementary approach would be large-scale training of advisory services to companion modeling approaches to engage with many farming communities across the region and the country into a game-based extension process of CA practices at the national level (Etienne, 2014). A third approach that would match well with the Cambodian tradition of rural theater would be to turn the lessons from the game into participatory theater (or forum theater – Botta et al. 2017) and engage larger village communities in the social learning process.

4.5 Conclusions

We gradually progressed from participatory diagnosis to action through the successive stages of (i) data collection from multiple sources, (ii) co-designing a game that integrates multiple perspectives and multiple scales and then (iii) collective experiments involving social learning. Using the RADA game, we learnt about constraints to adoption of innovative techniques and shared research findings with the farming communities. We identified windows of opportunity for agroecology, i.e. times when farmers are more willing to adopt soil conservation practices. We could discuss with local people how to change the 'rules of the game' towards more sustainable agricultural practices.

Next, we need to enlarge the circle of participants to the learning process by engaging with multiple stakeholder groups (up-scaling) and creating the conditions for replication in many locations (out-scaling) through capacity development of advisory services. Engaging stakeholders in landscape approaches to agroecology requires successive learning loops and long-term stewardship to transform the local institutions and social organizations. Under this condition only will the projects durably transform landscapes and livelihoods.

We did not project into future scenarios with the game through simulating additional rounds. However, we could observe from their play how each player anticipated their future. Based on the game results, the projected land uses in the study area will be dominated by orchards and grazing areas for cattle as these activities are considered less risky and require less labor. The areas of annual upland crops like maize and cassava will decrease in the near future, especially in case of delays in implementing the transformative landscape approach described above. A large part of the farming community will have no other option than to migrate again thus feeding the rural exodus from neighboring Thailand to the blooming garment industry in Cambodia.

Acknowledgements

We thank the farmers and the authorities in Rotonak Mondol district, Battambang province, who participated in this research. The Agence Française de Développement (AFD) through the ACTAE project (Towards an Agro-ecological Transition in Southeast Asia) provided financial support to the research reported in this paper.

Chapter 5

General discussion and conclusions

5.1 Consequences of a business-as-usual agricultural development scenario in Rotonak Monol District

The study investigated the complexity of rapid LUCC associated with the consecutive boom-bust cycles of commodity crops, such as maize and cassava. The agricultural development model based on the rapid expansion of annual upland crops with "green revolution" technology is obviously not sustainable. More recently, farming activities have evolved toward integration of orchards in agricultural landscapes, which is likely to generate further negative impacts.

5.1.1 Increased vulnerability of farming systems

The agrarian changes that occurred over the last two decades in Rotonak Monol have followed a pattern similar to what has been described in other areas of the Mekong Region (Bruun et al., 2017; Cramb et al., 2009; Jepsen et al., 2019; Meyfroidt et al., 2014). A pioneer crop (maize) supported by favorable market conditions and a blossoming agro-industry initially raised the enthusiasm of smallholder farmers and attracted migrants from across the country. The prevailing logic was to grasp the opportunity to generate a quick economic return. Maize cultivation expanded through till-based mono-cropping after deforestation. Markets ensuring the access to inputs and sale of outputs were organized by well-connected actors along the commodity chain, including micro-finance institutions (MFI). The initial results were very encouraging both in terms of yield and overall profitability. However, the promise of a bright maize-based future was short-lived for farmers. Yield levels quickly dropped and pest outbreaks increased due to mono-cropping practices. Land and labor productivities - measured as valued added per hectare and per active labor respectively – declined as a result. This productivity loss was compensated by the increased use of fertilizers and pesticides that incentivized indebtedness to MFIs.

A few years later, cassava emerged as a new boom crop, driven by market opportunities and the same trade actor-network connected to regional agro-industries. The opportunities cassava offered raised similar enthusiasm amongst farmers who were driven by the same logic: capturing short-term profit by adopting simple techniques to cultivate highly demanded crops. To some extent, cassava substituted maize but also resulted in a second wave of deforestation. Unfortunately, history repeated itself. After the first boom years, crop yield and profitability declined. The downside was even more pronounced as the forest frontier had progressively closed, impeding the expansion of agricultural land. The agricultural intensification process also further impacted the productive potential of land resources as repeated tillage induced soil fertility depletion and, generally speaking, land degradation (Bruun et al., 2017; Dressler et al., 2017; Kem, 2017; Montgomery et al., 2017; Touch et al., 2017).

These processes made the farming systems more vulnerable by limiting their capacity to adapt to further changes. Adding to these constraints, uncertainties beyond the farmers' control exacerbated the risks to which they were exposed: price volatility of agricultural commodities and weather uncertainty. Farmers are increasingly exposed to these risks that can easily put their livelihood in jeopardy. Farmers with enough resources manage to make ends meet but for those in distress due to indebtedness or land degradation, labor mobility outside agriculture is often the only coping mechanism (Diepart and Sem, 2018; Kelly, 2011; World Bank, 2015).

The farmers who can afford it moved to perennial tree crops and orchard plantations (i.e. mango and longan), driven again by the same boom crop logic. Orchards can accommodate degraded soils and the installation of irrigation systems required for off-season production can partly address the problem of rainfall variation. However, off-season production cannot always benefit from good market conditions and premium prices, which are also highly variable such as in early 2019 following a drop in price of longan fruits. The use of insecticides and fungicides also increased due to a lack of species diversity and integrated pest control. The drastic increase in orchard areas, and specifically off-season production for longan and some of mango orchards, raised concern over water resource availability and possible conflicts between water use for farming and households. During our surveys, most of commune heads in Rattanak Mondoul District expressed their concern over increased use of pesticides and water conflicts. Consequently, farming systems specializing in off-season orchard production are also vulnerable.

5.1.2 Homogenization of agricultural landscapes and differentiation of livelihoods

As farmers have largely shared the same enthusiasm for boom crops and tend to mimic each other, the socioecological vulnerability at farming system level is reproduced at the landscape level. Within less than a decade, the forests of Rotonak Monol have been turned to homogenous agricultural landscapes through maize and cassava monocropping (Kong et al., 2019). With the expansion of fruit tree plantations, a diversification process is observed from place to place consisting of remnants of hybrid maize, cassava fields, mango/longan orchards associated or intercropped with additional species such as papaya and banana. The recent trend towards tree crops could potentially maintain or restore the soil quality that has been degraded by unsustainable annual crop (maize and cassava) cultivation techniques based on intensive soil tillage (Kong et al., n.d.; Leakey, 2017; Maikhuri et al., 1997). However, plough-based management of the intercropping during the juvenile stage and increasing use of pesticides may induce additional environmental problems. In addition, the farmers claimed during the workshop of RADA game that mango plantations could be converted back to annual crops or another specie of orchards if its price falls too low (Chapter 4). Additionally, the current orchard expansion may reverse rapidly with the persistence of monocropping that reinforces the risks of pest outbreaks and water pollution. In short, simplified, homogenous agricultural landscapes are more sensitive to market variability and their ecological adaptive capacity to change is thus also affected.

All the farmers are not equally equipped to face and adapt to these transformations and their impacts are socially differentiated. The most vulnerable households, endowed with small agricultural landholding tend to lose proportionally more than others when the bust phase of the crop boom does hit (Diepart and Sem, 2018; Kong, n.d.; Mahanty and Milne, 2016). Over-indebtedness very often results in de-capitalization through land sale and/or in job-related migration (Diepart and Sem, 2018; Kem, 2017; Pilgrim et al., 2012). The income portfolio of this group of households progressively shifts from self-employed farming activities to wage labor. Another group of farmers managed to make ends meet but remains vulnerable, particularly to indebtedness. They also rely on wage labor and even job-migration in bad years, but tend to invest more in agriculture during good years (Kong, n.d.). A third category of producers has enough assets to absorb the shocks and to enlarge their landholding and agricultural operations. They are more involved in agricultural innovations. Their income is less dependent on job migration and wage labor and they tend to hire in labor instead. Even if they take advantage of opportunities offered by boom crops, they remain vulnerable to the drawback of the bust phase. These household types do not evolve independently, however, since agricultural changes transform the social relations of production between types. Labor-abundant and land-poor households tend to sell their labor to land-abundant households before turning to wage labor activities outside the village. These new labor relations are also associated with land market activities within communities and leading to a process of land concentration that is built-in within communities. This somewhat classical process of polarization (of land on the one hand and labor on the other) is exacerbated by outsiders (rich migrant farmers, urban dwellers) who are buying up land in the villages to become agricultural producers (Boulakia et al., 2013; Diepart and Dupuis, 2014; Diepart and Sem, 2018; Kem, 2017).

In such a context, a business-as-usual development scenario does not seem promising. Farmers have experienced the negative consequences associated with boom-bust cycles and are well aware of the recurrent associated issues. However, they are not in a position to break this cycle as they remain trapped in the logic of quick economic returns that overrides any longer-term environmental or social considerations. More fundamentally, their mindset is influenced by two main factors. For one thing, the actors that populate the commodity chains are well organized and well connected to pave the way to crop booms. In Cambodia, agricultural development policies also drive crop booms and there is little political support to promote and nurture alternatives. On the other hand, rural communities mainly consist of an assemblage of migrants who do not necessarily share the same history or a common vision to develop their territory. This lack of social cohesion limits the community's capacity to effectively learn from their boom crop experiences and take action to break the boom-bust cycles. Instead, it rather induces more individualist behaviors in time of hardship.

The status quo is characterized by tension between the propensity of people to look for the next boom crop, thus reproducing dead-end logic and the awareness, and at times willingness, of farmers to break the cycle. It is unlikely that another boom of annual upland crops will happen after cassava since the soil is already heavily depleted, production costs are increasing, the pest control functions of the ecosystem have deteriorated and the globalized market can no longer guarantee high prices over a long period as had occurred before with maize.

5.2 Toward an agro-ecological transition in the uplands of Cambodia

Since 2010, the PADAC project tried to break the maize boom-bust cycle through conservation agriculture (CA) alternatives. The lessons from the project that intervened both during the boom and the post-boom periods could help design appropriate intervention mechanisms and identify new avenues toward an agro-ecological transition away from the dead ends of the crop boom cycles.

5.2.1 Lessons learned from the 2009-2013 and 2014-2018 period

The PADAC project applied the DATE approach (Husson et al., 2016) by conducting an agrarian diagnosis (Bertrand, 2011) and implementing field experiments based on technical references developed in Kampong Cham Province (Central East Region) from 2004-2009 (Boulakia et al., 2010). A range of direct-seeding, mulch-based cropping systems (Séguy et al., 2012) have been evaluated for the main annual crops with cover/relay crops and needed machineries. The best-bet maize-based cropping systems were compared with conventional systems through on-farm testing by volunteer farmers involved in a pilot extension network (R. Kong et al., 2016). The innovative cropping systems were tested simultaneously in experimental fields and in the pilot extension network. However, the results did not meet the initial expectations of reversing the process of soil fertility depletion due to a number of important challenges. In Kong *et al.*, (n.d.), we translated these challenges into lessons for the exploration of development pathways and intervention mechanisms towards sustainable intensification.

One of the main challenges encountered was the fast changing market demand from pulse crops to maize on the pioneer front, and then from maize to cassava by the end of the maize boom. The market demand has always been a key driver of the agro-industrial sector. For instance, the remarkable increase of cassava cultivated areas in Cambodia from 2010s was also related to the drop of production due to the outbreak of mealybug in Thailand (Wyckhuys et al., 2018). Changing market opportunities become an issue when the rapid changes in the cropping and production systems are quicker than the minimum required time for evaluating environmental performances and impacts. Even at demonstration sites, where the project was designing diversified cropping systems with a large number of crops, it was difficult for researchers to have enough reactivity to follow the rapid changes in the cropping systems. The window of opportunities to adapt alternative cropping systems is extremely narrow (Castella, 2012).

Despite the subsidies provided by the project to buffer the risks (R. Kong et al., 2016) for innovative farmers who invested in crop diversification (main crops and cover/relay crops) these farmers were reluctant to apply new technical packages as long as the profitability of their overall farming systems was still acceptable. The farmers perceived these practices (i.e. canceling disc plowing, use of cover crops, and chemical fertilizers) as disruptive as compared to conventional crop management. They would only consider adopting innovations that allowed a clear, visible decrease in labor inputs and/or production costs with, as a direct result, a higher profitability of land and labor. The project adapted to these individual decision-making strategies by changing its approach to support innovation from subsidizing a full technical package to providing a no-till planting service associated with an advisory service from 2013 onward. The project staff played the role of a private service provider for sowing maize with a no-till planter and for providing technical backstopping. Maintaining the dynamics of the farmer network around elements of CA innovation i.e. no-till planter service and provision of a range of technical options on a volunteer basis maintained a learning ground for the farmers and other local actors.

The lack of development operations jointly designed and implemented with local actors were definitively a main constraint to achieve higher impacts. This advocates for maintaining on-farm experimental fields to play the role of “technological beacon,” where key co-designed cropping systems are compared with one another over several years, alongside past and present farming practices. Such an approach would demonstrate the performances of the innovative cropping systems: (i) after the conversion, when soil conditions gradually improve; and (ii) across varying climatic conditions during successive years.

5.2.2 Lessons learned and perspectives from the RADA game

The use of role-playing games revealed the role of the PADAC project in changing farmers' perceptions and social learning which could hardly be investigated through individual interviews or group discussions. For example, we showed that the willingness of farmers to adopt CA-based cropping systems strongly relates to their perception of technical and economic risks and declining productivity (Chapter 4). Clearly, the quality of the participatory processes was linked to their understanding of the benefits of soil conservation practices. The RADA game also revealed the need for more holistic approaches to innovation, notably to integrate a larger diversity of options addressing all components of farming systems. There is a need to generate and integrate new technical and organizational knowledge in order to negotiate solutions, explore opportunities and learn in different combined and integrated ways, thus facilitating the emergence of collective actions (van Mierlo et al., 2017).

The RADA game did not explicitly explore scenarios including agroecological technical and organizational options for the future. Taking advantage of the current diversification process in the upland landscapes (combination of annual and perennial crops), a number of agroecological options, such as agroforestry systems and crop-livestock integration could be tested to improve agronomic efficiency, while investing in natural resource management (Leakey, 2017; Maikhuri et al., 1997; Shi and Li, 1999). However, there are no one-size-fits-all or free-fit innovations. Studies on agricultural innovation promote co-production of knowledge to stimulate innovation niches and to foster the transition to sustainable intensification (Systems et al., 2018). The RADA game could help explore such transition scenarios by mobilizing the lessons learnt collectively since the PADAC period.

The results of the RADA game (Chapter 4) confirmed the positive impact of the PADAC project on (i) soft skills development in relation to technical knowledge (i.e. soil conservation, risks management) and (ii) organizational capacity with fire control as an example. Even though the numbers of CA households and hectares are low, farmers evolved in their understanding of CA and changed their mindsets and attitudes in relation to boom crops when compared with the non-CA farmers/villages. The work of the PADAC team allowed for the emergence of a hybrid network of researchers, extension staff and farmers through their joint experiences on a large number of crops, cropping patterns and tools they still mobilize several years after. The technical skills built over the years represent a rich asset for the Cambodian agriculture sector that is valued through different learning approaches: e-learning (www.iperca.org) and capacity development through the newly created CA national network (https://ali-sea.org).

However, the weaknesses of social organizations and the prevalence of farmers' boom-crop mindsets were observed repeatedly during the games conducted in both CA and non-CA villages. It confirmed the lack of social cohesion within the farming community to collectively discuss and explore solutions. As recent migrants in a pioneer front region, farmers tend to work and decide individually as they share different backgrounds and histories. Mostly, they mimic the land use decisions and farming practices of their successful or influential neighbors through observation, without discussion or collective dialogue. As long as farmers remain in the mindset of commodity production (Bernstein, 1977), a higher degree of farm diversification is difficult to achieve. Other actors of the value-chains should drive the change toward agroecology practices by allocating a price premium to agroecological products. Without any acknowledgement of the quality of agroecology products, farmers may follow the trends of new boom crops associated with a land concentration process. The increase in orchard areas questions not only the durability of the market demand but also that of labor and water resource availability. Additional studies should address these expected changes and how to deal with a twofold objective of providing water access for residents and water for agricultural purposes as well as with labor requirements for the production and post-harvest operations and the current outflow of labor for migration work. The RADA game could be potentially scaled up to village and commune levels using participatory theater approaches (Botta et al., 2017) to raise awareness of land degradation, adverse consequences of boom and bust cycles, as well as introducing alternative systems.

5.3 General conclusion

This PhD research brought together three integrative approaches, namely land use/cover change analysis, typologies and trajectories of farming systems, and participatory simulations with a role-play game, into a single analytical framework to understand the complex and rapid agricultural changes and repeated cycle of boom crops in a pioneer front region. The land use/cover change (LUCC) analysis permitted us to characterize and quantify the changes, as well as to define its drivers and actors so that relevant intervention measures could be proposed. The farming system analysis was used to assess the diversity of farming systems according to their innovation constraints and opportunities. The participatory simulation game recreated virtually the context of farmers' decision making prevailing during the maize boom to explore land management scenarios and engage participants in collective learning (Etienne, 2014). Each approach has its own advantages and constraints. By combining them we developed a holistic approach capable of capturing the very rapid changes that completely transformed the landscapes and livelihoods over only a few years. The speed of the changes we were addressing was a major methodological challenge. Indeed, we designed our framework to capture the transformative wave, its drivers and its impacts, in a meaningful way for local actors to learn lessons and act on them to ultimately contribute to sustainable agricultural intensification. It was highly challenging to integrate the three approaches in this PhD research since I had to study all three approaches to be able to synergize them. The study designed an innovative framework and tested it in real conditions to investigate boom and bust cycles of commodity crops in rapidly changing contexts of pioneer fronts (Figure 5). The systematic combination of qualitative and quantitative methods across multiple scales (i.e. from plot to farm to landscape levels) and periods added value to the overall scientific approach.

Remote sensing data analysis unveiled dramatic LUCC, with forestland massively converted to agriculture, and agricultural land uses in fast transition from pulse crops to maize, from maize to cassava, and from cassava to orchards. The LUCC analysis was based on convergent information collected from different data sources using the framework adopted from (Geist and Lambin, 2002). We could not use statistical multivariable analysis due to the lack of consistent data across scales and periods (Chapter 2) nor land use modeling due to the paucity and heterogeneity of available data sets (Ornetsmüller et al., 2018).

The farming systems analysis characterized different types of land users and investigated their decision making processes and capacities to innovate in relation with their farm structure and functioning. We used multivariable statistical analysis to produce a structural typology (Tittonell, 2014) with complementary data from individual retrospective interviews of representatives from each identified farm type to produce a functional typology. This multi-dimensional knowledge of farm resources and socioeconomics was a precious addition to other farm typologies based on qualitative methods for the Northwestern Uplands of Cambodia (Diepart and Sem, 2018). Nevertheless, as a snapshot of farming diversity in a given time, the validity of the farm typology is extended by the combination of slow and fast moving variables (Berre et al., 2016). In a context of fast economic growth such as in Cambodia (Dixon, 2018a), it was important to carefully select relevant slow variables for the structural typology and confirm the typology using expert knowledge of long term policy and innovation dimensions (Falconnier et al., 2015). This typology may be used as a reference for longitudinal studies in the future.

The RADA simulation game helped elicit famers' decisions by putting them in a virtual decision making situation. Decision making processes were investigated on a real time basis using the role-playing game. The game revealed how farmers mobilize their existing social networks in adapting and adopting CA techniques. It showed the importance of the service provision using a no-till planter provided by the project triggering and maintaining innovation. The triangulation of results from successive gaming sessions gradually improved our understanding of innovation contexts and helped disentangle a complex reality. Still, we faced some limitations with this gaming approach, as the game was played with only one set of players / farmers in each village. Increasing the number of gaming sessions would definitely improve its credibility, but may also increase the financial and time requirements, and may create research fatigue in the target villages. Translating the game into a participatory theater show (Botta et al. 2017) may permit involving the entire village audience in the collective exploration of sustainable intensification pathways. It may become a cost-effective way for both scaling up lessons from the game and validating its outputs. It may also help explore future scenarios and problem solving pathways with a larger audience, i.e. service provision for CA practices, establishment of improved pastures or permanent cover crops for orchard plantations

(Suphanchaimart, Wongsamun and Panthong, 2005; Abrami *et al.*, 2010; Barnaud, Bousquet and Trebuil, 2008).

As this thesis demonstrates, and more generally in the field of agricultural development, farmers are key agents of change. As a result, the household is the main unit of analysis even though, in the context of market-based farming, individual decisions are increasingly influenced and impacted by the changes in markets and policies at the global scale (Friis and Nielsen, 2014). This study focused exclusively on farmers' decision making, which is influenced by market opportunities and economic returns taking into account risks and management capacities. While such an understanding is necessary, it may not be sufficient to solve the current farming problems, including soil depletion and declines in productivity, increasing price fluctuations and climate related risks.

Even organized in cooperatives, farmers have to deal with an increasing number of stakeholders (i.e. traders, input suppliers, processing factories, and micro credit institutions) and uncertainties along the value chains. The market drives most of the changes observed in the recent years and transforms all components of the farming systems. In a context of globalization, farming systems have rapidly evolved to be more complex with more actors and dimensions at the landscape scale (Dixon, 2018a; Milestad *et al.*, 2012). Future studies should include the identification of agro-ecology based value chains for current commodities (maize, cassava, mango, and longan) and cover crops. Improving agro-ecology based value chains will require collective actions, communication platforms or hubs that involve stakeholders in exchanges and negotiations in order to reach a consensus that yields benefits for everyone (Birachi et al., 2013). This could be called an innovation platform (Schut et al., 2017; Tui Homann-Kee et al., 2013) as it aims to support the agro-ecology transitions for sustainable intensification by changing the roles and perceptions of farmers from innovation adopters/takers to collaborators, owners and leaders, and of researchers/technicians from innovation leaders/prescribers to simply facilitators (World Bank, 2012). Such an approach could succeed if all the involved stakeholders perceive on one hand that they have common problems and close interdependence, and on the other hand that they own the collective actions. As such, they would be willing to fully participate in the collective learning process (Berthet and Hickey, 2018; Schut et al., 2018).

Furthermore, future studies should include a social network analysis and mapping of the stakeholders involved in the multi-stakeholder platforms (Flor et al., 2016; Schut et al., 2016a; Triomphe et al., 2018). The experiences from the Central African Highlands show that poor or slow development of organizations creates economic and institutional constraints for sustainable intensification (Schut et al., 2016b). Therefore, it is essential to develop an anthropological dimension to our research and analyze consistently the social and institutional dimensions of innovation (Arensen, 2012).

Appendixes

Appendix 1: Landsat images used in the study

Year	Acquired date	Sensor	Band and spatial resolution	Reference WRS Path/Row	Data projection
1976	17/01/1976	Landsat-2 MSS	V, R, PIR1 (80 m)	137/51	WGS84-UTM 48N
1997	22/12/1997	Landsat-5 TM	B, V, R, PIR (30 m)	127/51	WGS84-UTM 48N
1997	29/12/1997	Landsat-5 TM	B, V, R, PIR (30 m)	128/51	WGS84-UTM 47N
2002	23/12/2003	Landsat-5 TM	B, V, R, PIR (30 m)	127/51	WGS84-UTM 48N
2002	30/12/2003	Landsat-5 TM	B, V, R, PIR (30 m)	128/51	WGS84-UTM 47N
2006	18/02/2005	Landsat-5 TM	B, V, R, PIR (30 m)	127/51	WGS84-UTM 48N
2006	27/02/2005	Landsat-5 TM	B, V, R, PIR (30 m)	128/51	WGS84-UTM 47N
2010	12/01/2009	Landsat-5 TM	B, V, R, PIR (30 m)	127/51	WGS84-UTM 48N
2010	21/01/2009	Landsat-5 TM	B, V, R, PIR (30 m)	128/51	WGS84-UTM 47N
2016	26/02/2016	Landsat-8 OLI- TIRS	B, V, R, PIR, MIR (30 m) PAN (15 m)	127/51	WGS84-UTM 48N
2016	14/04/2016	Landsat-8 OLI- TIRS	B, V, R, PIR, MIR (30 m) PAN (15 m)	128/51	WGS84-UTM 47N

Appendix 2: Predetermined LULC classes on the basis of supervised classification

No.	Class name	Description
1	Dense forest	Forestland of native species without visible indication of human activities and significant disturbance of ecological processes.
2	Degraded forest	Forestland of native species with a clear visibility of human activities and significant disturbance of ecological process.
3	Bush	Wood and shrub land either evergreen or inundated, which also include the bamboo.
4	Grass	Non-woody bush, grass, bared land
5	Tree crops	Tree crops such as rubber trees, cashew nut, and orchard
6	Annual upland crop	Annual upland crops such as cassava, maize, and upland rice
7	Paddy rice	Lowland rice both rain-fed and irrigated
8	Artificial	Residential, commercial, industrial, and roads
9	Water	Rivers, leaks, ponds and reservoirs

Appendix 3: Accuracy assessment of classification results based on confusion matrix

Year	Overall Accuracy (%)	Kappa
1976	93	0.92
1997	86	0.85
2002	85	0.84
2006	87	0.86
2010	83	0.82
2016	74	0.73

Appendix 4: Matrix of LUCC analysis between 1997 and 2016

1997	2016																					
	Dense forest		Degraded forest		Bush		Grass		Annual upland crops		Paddy rice		Tree crops		Artificial		Water		Unclassified		1997	
	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Dense forest	643.6	99	157.9	82	92.3	35	29.5	22	941.8	54	8.4	4	86.9	55	4.4	14	0.0	0	4.2	40	1969.1	58
Degraded forest	4.5	1	32.8	17	156.6	60	87.1	64	687.6	40	100.3	53	62.1	39	15.9	51	0.0	0	5.3	50	1152.3	34
Bush	0.1	0	1.0	1	11.3	4	18.6	14	94.0	5	46.3	24	7.5	5	0.1	0	0.0	0	1.0	10	180.1	5
Grass	0.0	0	0.1	0	0.3	0	0.5	0	4.4	0	7.2	4	0.6	0	1.1	4	0.0	0	0.0	0	14.2	0
Annual upland crops	0.0	0	0.2	0	0.3	0	0.3	0	5.1	0	2.0	1	2.2	1	1.3	4	0.0	0	0.0	0	11.5	0
Paddy rice	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	25.0	13	0.0	0	0.0	0	0.0	0	0.0	0	25.0	1
Tree crops	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0
Artificial	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	8.4	27	0.0	0	0.0	0	8.4	0
Water	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	64	100	0.0	0	63.7	2
Unclassified	0.1	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.2	0
2016 Total	648	100	192	100	261	100	136	100	1733	100	189	100	159	100	31	100	64	100	11	100	3424	100
2016 (%)	18.9		5.6		7.6		4.0		50.6		5.5		4.7		0.9		1.9		0.3			

Appendix 5: Expansion of road network with different road types

District	Road type	2001	2005	2011	2014
Pailin	Asphalt (km)	25	2	30	na
Sala Krau		0	0	18	na
Rotonak Mondol		0	35	34	145
Samlaut		0	0	0	0
Total		25	37	82	145
Pailin	Laterite (km)	2	96	4	na
Sala Krau		10	29	54	na
Rotonak Mondol		53	168	68	421
Samlaut		10	164	43	727
Total		76	458	169	1148
Pailin	Dirt (km)	62	163	370	na
Sala Krau		98	227	321	na
Rotonak Mondol		53	531	728	777
Samlaut		231	457	858	648
Total		443	1378	2277	1425
Total		544	1873	2529	2719

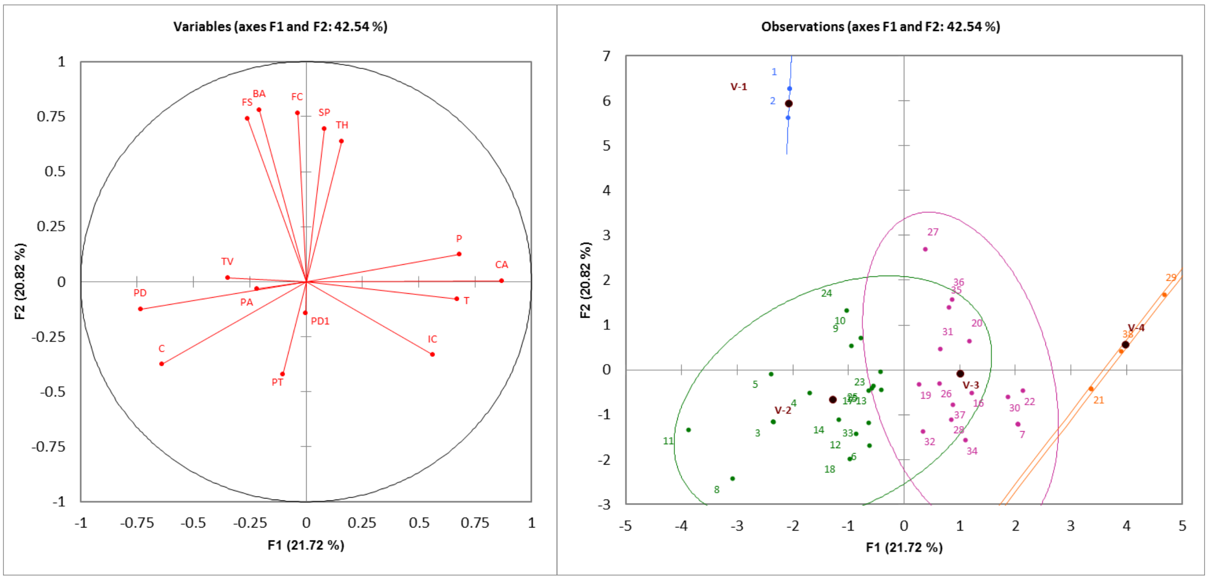
Note: na = not available data

Source: MPWT & JICA (2003), MLMUPC (2005), LICADHO (2011) and PDLMUPC (2014)

Appendix 6: Survey methods and sampling procedures in 10 study villages of Rotonak Mondol District

<table>
<tr><td rowspan="2" colspan="2">Description</td><td colspan="3">Survey methods</td></tr>
<tr><td>Semi-structured interview</td><td>5 focus group discussions</td><td>In-depth interview</td></tr>
<tr><td rowspan="6">Respondents</td><td>Number participants</td><td>19</td><td>48</td><td>95</td></tr>
<tr><td>Female</td><td>5</td><td>8</td><td>19</td></tr>
<tr><td>Age (years)</td><td>53 (±9)</td><td>49 (±8)</td><td>46 (±13)</td></tr>
<tr><td>Education (school years)</td><td>6.5 (±3.3)</td><td>7.6 (±2.3)</td><td>4.5 (±3.5)</td></tr>
<tr><td>Socio-economic back-ground</td><td>Elder villagers and local officials</td><td>Elder villagers and local officials</td><td>- Upland crop-based smallholder farm
- Upland crop-based large-scale farm
- Off-farm income dominated farm
- Paddy-based farm</td></tr>
<tr><td>Selection procedure</td><td>Snowball selection</td><td>Snowball selection</td><td>Stratified random sampling</td></tr>
<tr><td colspan="2">When</td><td>January 2016</td><td>April 2016</td><td>December 2016</td></tr>
<tr><td colspan="2">Duration</td><td>1-2 hours</td><td>3-4 hours</td><td>1.5-2 hours</td></tr>
<tr><td colspan="2">Contents</td><td>Village history
In-migration process
Land access and conversion of forest to agricultural land
Access to market and credit
Technical and organizational innovations
Perception on crop productivity and land degradation</td><td>Important changes of land use and land cover
Drivers of changes: causes and factors
Interactions within and linkages between causes and factors
Defining levels (strong, medium, weak) of importance for each interaction and linkage</td><td>Migration
Farm's land, labor, finance, and asset
Farm's activities and incomes
Land uses
Farming practices and innovation
Farming constraints
Access to technology, credit, and market</td></tr>
</table>

Appendix 7: Distribution of the villages in the village PCA (left) and the AHC (right).



Appendix 8: Characteristics of village types

Village cluster	V-1	V-2	V-3	V-4	Total	P-value
Cluster name	Urban village	Lowland diversified village	Upland diversified village	Upland intensified village		
Number	2 (5%)	18 (47%)	15 (40%)	3 (8%)	38	
Demography						
Total household	459	225	245	357	256	.053
Economy						
%Female in services	35.9	6.3	5.7	6.5	7.7	.000
%Shop	6.5	1.3	2.2	2.6	2.0	.107
Household asset						
%Family car	6.9	1.1	1.5	2.0	1.6	.000
%Cattle	12.9	49.1	17.7	5.6	31.3	.000
%TV	72.3	59.5	46.5	43.8	53.8	.338
%Tractor	1.1	1.4	2.2	7.2	2.2	.000
%Power tiller	3.0	8.7	7.2	5.2	7.5	.388
%Planter	0.0	0.0	0.4	4.1	0.5	.000
Agricultural input						
%Insecticides	17.1	55.8	73.8	95.8	64.0	.004
Land use						
%Built-up area	16.9	0.9	0.9	0.8	1.7	.000
%Crop area	37.6	42.8	76.5	92.4	59.7	.000
%Paddy area	30.5	27.4	5.1	0.3	16.6	.001
%Plantation area	2.5	13.2	5.3	2.7	8.7	.291
%Paddy<1ha	2.1	19.3	13.9	25.5	16.7	.474

Appendix 9: Assessment of economic performances of crop and livestock systems

Cropping systems:

- Gross Output (GO) = [total quantities produced] x average selling price on the local market
- Gross Value-Added (GVA) = GO - Intermediate Inputs (II)

II = monetary value of the seeds, chemical inputs and services used during one year of production with this cropping system.

This economic value already allows interesting comparisons to be made by calculating:

- GVA per unit area: GVA / ha
- GVA per working-day (based on the total quantity of labor required): GVA / wd (wd: working-day)
- Gross Remuneration of family labor: (GVA – wages paid to employees) / (wd carried out by family members)

Livestock rearing systems:

- Gross output (GO)= ordinary annual output based on the technical results of the herd and the use made of the products within this livestock rearing system
- Gross Value-Added (GVA) = GO - Intermediate Inputs (II)

II = sum of all of the costs linked to the breeding practices, feeding the animals, veterinary costs care, maintenance, etc.

Appendix 10: Definition of organizational and technical innovations

No.	List of innovations	Description of innovations
Organizational innovations		
1	Member of any group (farmers' cooperative, contract farming…that impacts on decision making to the changes)	Deciding to be a member of any farmers' group is considered part of organizational innovation. The group could be official or unofficial i.e. cooperative, contract farming, saving group…etc. created for collective actions and benefits.
Technical innovations		
1	No-tilling and no burning	Residues of precedent crops are kept on the field and used as mulching for preceding crops without tilling and burning, for instance keeping residues of precedent maize previous season as mulch for preceding maize next season.
2	Cover crops (pigeon pea…etc.)	Any leguminous and gramineae species grown in association, succession or rotation with the main crops for the purpose of soil improvements and breaking pest cycles.
3	Inter-cropping (i.e. orchards with annual crops or vegetables)	Growing vegetables in inter-row of orchards (mango or longan) plantation either during 2-3 first years of unproductive stage or permanent period for the benefits of improving the water and fertilizer efficiency. The intercropping annual crops such as maize and cassava is not considered as an innovation since it is a general practice for all farm types.
4	Crop succession (whatever succession with different species i.e. mungbean/maize, maize/mungbean…)	Growing two or more different species in successive cropping systems within a cropping season for example mungbean is precedent or preceding crop for maize as the main crop.
5	Crop rotation (whatever rotation with different species and > 1Y fallow i.e. maize/cassava…)	Growing two or more different species in rotational cropping systems for a two-year or more rotation for instance biannual rotation of maize and cassava.
6	Elements of SRI (direct seeding, young seedling, spacing…)	Any practices of system of rice intensification (SRI) principles (Mishra et al., 2006; Ly et al., 2012) to express the agronomic and genetic potential of rice production for instance translating fewer younger seedlings.
7	Improved pasture (i.e. planting new grass or tree species)	Using high nutritious fodder species either single or mixed gramineae and leguminous species to improve the pasture.
8	Others	

Appendix 11: Characteristics of farm and village type in Rotonak Mondol District

Village typology (no. 38)			
Urban Village (5%)	Lowland-Diversified Village (47%)	Upland-Diversified Village (40%)	Upland-Intensive Village (8%)
Densely populated villages with residential and commercial areas, and few agricultural activities	Large paddy area and most households owning cattle. Diversified rice-based farming system with low level of intensification using agrochemicals and machinery	Larger upland than paddy areas. Diversified upland crops-based farming system with moderate level of intensification using agrochemicals and machinery	Whole village territory is upland area. Intensive farming using agrochemicals and large-scale machinery such as tractors, planters, etc.
Farm typology (no. 365)			
Upland crop-based smallholder farm (25%): FT-1	Upland crop-based large farm (20%): FT-2	Off-farm income dominated farm (35%): FT-3	Paddy based farm (20%): FT-4
Low to medium resource farms. Diversified activities including paddy, upland crops and off-farm. The farming is based on upland crops with moderate intensification.	High resources farms with intensive upland crop production. Complementary cash income from off-farm activities based on skilled work or service provision i.e. credit, plowing services, etc.	Low resources farms. The livelihood systems are mainly based on off- farm activities including out-migration work. Little farming-based crop production.	Low to medium resources farms with cattle-rice integration. The livelihood systems are based on rice production for household food security. Off-farm activities for cash income generation.

Appendix 12: Methods and sampling procedures

Description	Study methods in Rotonak Mondol District								
						Co-designing RADA game		Using RADA game	
	Semi-structured interview	5 focus group discussions	Household questionnaire survey	In-depth interview following the questionnaire survey	In-depth interview for CA adoption	Game prototyping	Game testing	Game workshop	Following up survey
Number participants	19	48	365	95	165*	7	30	54	48
Female	5	8	60	19	30	0	8	14	12
Background	Elder villagers and local officials	Elder villagers and local officials	Random households	29 FT-3, 19 FT-4, 22 FT-1, 25 FT-2 11 farmers involve in CA project	34 continued CA farmers (15 FT-1, 19 FT-2), 131 drop-off CA farmers (31 FT-3, 5 FT-4, 65 FT-1, 30 FT-2)	Agronomist, socio-economist, extension agent	6 authorities, 6 farmers from each farm type	6 authorities, 12 farmers from each farm type	12 farmers from each farm type
Selection procedure	Snowball selection	Snowball selection	Random sampling	Stratified random sampling	All	Purpose for authorities and game team, stratified and purpose for the farmers			
When	January 2016	April 2016	February 2016	December 2016	February 2017	December 2017		January 2018	
Duration	1-2 hours	3-4 hours	1.5-2 hours	1.5-2 hours	1 hour				
Contents	- Village history - Land use and land cover:	- Important changes of land use and land cover	- Household composition, originality, and education	- Migration - Farm's capital: land, labor,	- Reasons for experience, drop-off, and/or continue practicing	- Integrating knowledge for conceptual model of LUCC	- Refining the game protocol, parameter, rules and rounds.	- Implementing systematically the game session following the	- Checking if the play is self-realistic

	changes and drivers - In-migration process - Land access and conversion of forest to agricultural land - Access to market and credit - Technical and organizational innovations - Perception on crop productivity and land degradation	- Drivers of changes: causes and factors - Interactions within and linkages between causes and factors - Defining levels (strong, medium, weak) of importance for each interaction and linkage	- Farm resources and asset - Land uses and production systems including off-farm activities - Experiences of innovative practices and reasons	finance, and asset - Farm's activities and incomes - Land uses - Farming practices and innovation - Farming constraints - Access to technology, credit, and market	the CA techniques	- Prototyping the game which is realistic and playable	- Finalizing procedures to facilitate, monitor, and collect data	protocol and procedure	- Finding reasons behind decisions during the play

Note:
*: We visited all farmers who used to or were currently engaged with the CA project.
FT-1: Upland crop-based smallholder farm
FT-2: Upland crop-based large-scale farm
FT-3: Off-farm income dominated farm
FT-4: Paddy-based farm

Appendix 13: Parameters of the RADA Game

Appendix 13.1: Crop production parameters

Parameters of crop activities (Round 1-3)

Crop	Cropping	Round 1						Round 2						Round 3					
		Labor[+]			Income	Risk by dice		Labor			Income	Risk by dice		Labor			Income	Risk by dice	
		AT	PT	TT		Rain	Price	AT	PT	TT		Rain	Price	AT	PT	TT		Rain	Price
Paddy rice		3.0			0.6				3.0		0.6				1.0		0.6 1.0 if F		
Paddy rice																			
Upland rice		6.0			0.8				6.0		0.8				6.0		0.8 1.0 if F		
Peanut	1st	9.0			1.0				9.0		1.0				9.0		1.0		
Peanut	2nd								9.0		0.6				9.0		0.6 1.0 if F		
Peanut	3rd														9.0		0.2 1.0 if F		
Soybean		6.0			2.0	If 1-2 -> -0.2[*]			6.0		2.0	If 1-4 -> -1.0			6.0		2.0	If 1-4 -> -1.0	
DS Mungbean		6.0			0.8	If 1-3 -> -0.2			6.0		0.8	If 1-3 -> -0.2			6.0		0.8	If 1-4 -> -0.2	
RS Mungbean		6.0			0.8				6.0		0.8				6.0		0.8		
Sesame		6.0			0.8	If 1-3 -> -0.2			6.0		0.8	If 1-3 -> -0.2			6.0		0.8	If 1-4 -> -0.2	
Chilli		9.0			1.2			9.0	6.0		1.2			9.0	6.0		1.2		
DS Maize-CT	1st								1.5		1.5	If 1-3 -> -0.5					1.5		
	2nd														1.5	1.0	1 1.5 if F	If 1-4 -> -0.5	
	3rd																0.5 1.0 if F		
RS Maize-CT	1st								1.5		3.0						3.0		
	2nd														1.5	1.0	2 2.5 if F	If 1-3 -> -0.5	If 1-3 -> -0.5
	3rd																1.5 2.0 if F		
Maize-CA full	1st-3rd CT																		
RS Maize-CA planter	1st-2nd CT																		
	3rd																		
Cassava	1st																		
Cassava	2nd																		
Longan off-season																			
Mango off-season																			
Longan local																			
Vegetables																			
Supplementary parameters:																			
Family expense (million riel/person)		0.2						1						2					
Labor for cattle (button)		0-4 cattle -> 3 buttons 5-8 cattle -> 6 buttons …						0-4 cattle -> 3 buttons 5-8 cattle -> 6 buttons …						0-4 cattle -> 3 buttons 5-8 cattle -> 6 buttons …					
Grazing capacity (cattle/cell)		If Crop land -> 4 If Non-crop land -> 8 If Pasture -> 12						If Crop land -> 4 If Non-crop land -> 8 If Pasture -> 12						If Crop land -> 4 If Non-crop land -> 8 If Pasture -> 12					

Note:
- AT: Animal and manual based farming; PT: Power tiller and pesticides based farming; TT: Tractor and pesticides based farming; F: fertilizing
  DS: Dry season; RS: Rainy season; CT: Conventional tillage practice; CA: Conservation agriculture techniques
- Income is calculated in million riel (1 million KHR is about 250 USD)
- + labor is counted by number of button (1button = 2 man.months) representing the maximum area that an average farm labor could cultivate per cell/hectare
- * risk is managed by drawing the dice meaning that if the dice is from 1 to 2, the income will be deducted 0.2 million riels

Parameters of crop activities (Round 4-6)

Crop	Cropping	Round 4						Round 5						Round 6					
		Labor+			Income	Risk by dice		Labor			Income	Risk by dice		Labor			Income	Risk by dice	
		AT	PT	TT		Rain	Price	AT	PT	TT		Rain	Price	AT	PT	TT		Rain	Price
Paddy rice			1.0		0.6 1.0 if F				1		0.6 1.0 if F				1		0.6 1.0 if F		
Paddy rice				1.0	1.5					1.0	1.5					1.0	1.5		
Upland rice			6.0		0.8 1.0 if F				6.0		0.8 1.0 if F				6		0.8 1.0 if F		
Peanut	1st		9.0		1.0				9.0		1.0				9		1.0		
Peanut	2nd		9.0		0.6 1.0 if F				9.0		0.6 1.0 if F				9		0.6 1.0 if F		
Peanut	3rd		9.0		0.2 1.0 if F				9.0		0.2 1.0 if F				9		0.2 1.0 if F		
Soybean			6.0		2.0	If 1-4 -> -1.0*			6.0		2.0	If 1-4 -> -1.0			6		2.0	If 1-4 -> -1.0	
DS Mungbean			6.0		0.8	If 1-4 -> -0.2			6.0		0.8	If 1-5 -> -0.4			6		0.8	If 1-5 -> -0.8	
RS Mungbean			6.0		0.8				6.0		0.8				6		0.8		
Sesame			6.0		0.8	If 1-4 -> -0.2			6.0		0.8	If 1-5 -> -0.4			6		0.8	If 1-5 -> -0.8	
Chilli			6.0		1.2				6.0		1.2				6.0		1.2		
DS Maize-CT	1st		1.5	1.0	1.5	If 1-5 -> -0.5			1.5	1.0	1.5	If 1-5 -> -0.5			1.5	1	1.5	If 1-5 -> -0.5	
	2nd				1 1.5 if F						1 1.5 if F						1 1.5 if F		
	3rd				0.5 1.0 if F						0.5 1.0 if F						0.5 1.0 if F		
RS Maize-CT	1st		1.5	1.0	3.0	If 1-3 -> -0.5	If 1-3 -> -0.5		1.5	1.0	3.0	If 1-4 -> -0.5	If 1-4 -> -0.5		1.5	1	3.0	If 1-5 -> -0.5	If 1-5 -> -0.5
	2nd				2 2.5 if F						2 2.5 if F						2 2.5 if F		
	3rd				1.5 2.0 if F					1.0	1.5 2.0 if F						1.5 2.0 if F		
Maize-CA full	1st-3rd CT			1.0	3.0	If 1-3 -> -0.5	If 1-3 -> -0.5			1.0	3.0	If 1-4 -> -0.5	If 1-4 -> -0.5			1	3.0	If 1-5 -> -0.5	If 1-5 -> -0.5
RS Maize-CA planter	1st-2nd CT			1.0	3.0	If 1-3 -> -0.5	If 1-3 -> -0.5			1.0	3.0	If 1-4 -> -0.5	If 1-4 -> -0.5			1	3.0	If 1-5 -> -0.5	If 1-5 -> -0.5
	3rd				2.5						2.5						2.5		
Cassava	1st									3.0	4.0	If 1-3 -> 3.0				3	4.0	If 1-5 -> -0.5	If 1-5 -> -1.0
Cassava	2nd																2.5 3.0 if F		
Longan off-season														14.0			20.0	If 1-3 -> -8.0	
Mango off-season														14.0			20.0	If 1-3 -> -8.0	
Longan local														4.0			8.0		
Vegetables								12.0			14.0	If 1-3 -> 7.0		12.0			14.0	If 1-3 -> -7.0	
Supplementary parameters:																			
Family expense (million riel/person)		2						3						4					
Labor for cattle (button)		0-4 cattle -> 3 buttons 5-8 cattle -> 6 buttons …						0-4 cattle -> 3 buttons 5-8 cattle -> 6 buttons …						0-4 cattle -> 3 buttons 5-8 cattle -> 6 buttons …					
Grazing capacity (cattle/cell)		If Crop land -> 4 If Non-crop land -> 8 If Pasture -> 12						If Crop land -> 4 If Non-crop land -> 8 If Pasture -> 12						If Crop land -> 4 If Non-crop land -> 8 If Pasture -> 12					

Note:
- AT: Animal and manual based farming; PT: Power tiller and pesticides based farming; TT: Tractor and pesticides based farming; F: fertilizing
  DS: Dry season; RS: Rainy season; CT: Conventional tillage practice; CA: Conservation agriculture techniques
- Income is calculated in million riel (1 million KHR is about 250 USD)

- + labor is counted by number of button (1button = 2 man.months) representing the maximum area that an average farm labor could cultivate per cell/hectare
- * risk is managed by drawing the dice meaning that if the dice is from 1 to 4 the income will be deducted 1.0 million riels

Appendix 13.2: Household investment parameters

Parameters of investment activities

Investment	Round 1 and 2				Round 3 and 4				Round 5 and 6			
	Labor+	Cost	Income	Risks	Labor	Cost	Income	Risks	Labor	Cost	Income	Risks
Cattle buy/sale		0.6	0.6			1	1			2	2	
Cattle income			0.3	If 1-2 -> -0.1*			0.5	If 1-2 -> -0.1			1	If 1-2 -> -0.2
Pasture installation					3	0.2			3	0.2		
Cattle income with pasture							0.6	If 1-2 -> -0.1			1.2	If 1-2 -> -0.2
Labor sell**	per month	0.2	0.2	If 5-6 -> sale 100% If 3-4 -> sale 50% If 1-2 -> sale 25%	per month	0.4	0.4	If 5-6 -> sale 100% If 3-4 -> sale 50% If 1-2 -> sale 25%	per month	0.6	0.6	If 5-6 -> sale 100% If 3-4 -> sale 50% If 1-2 -> sale 25%
Labor buy	per button	0.2	0.2		per button	0.4	0.4		per button	0.6	0.6	
Upland buy/sell		4	4			8	8			12	12	
Paddy buy/sell		2	2			4	4			6	6	
Upland rent		0.2	0.2			0.4	0.4			0.6	0.6	
Paddy rent		0	0			0.4	0.4			0.4	0.4	
Power tiller		6	6			8	8			8	8	
Rent power tiller		0.2	0.2			0.2	0.2			0.2	0.2	
Credit interest		Δ	100%	If 1 -> lose 10%		Δ	30%	If 1 -> lose 10%		Δ	18%	If 1-2 -> lose 10%
Charcoal production	1		0.2		1		0.2		1		0.8	
NTFP collection					1		0.2					
Build house		2				6				12		
Motobike		3				3				3		
Longan installation									3	8		
Renting longan plantation										10		
Mango installation									3	2		
Renting mango plantation										8		
Local longan installation									3	2		
Fertilizer application						0.2				0.2		

Note:
Income and cost are calculated in million riel (1 million KHR is about 250 USD)
+ labor is counted by number of button (1button = 2 man.months) representing the maximum area that an average farm labor could cultivate or do
* risk is managed by drawing the dice meaning that if the dice is from 1 to 2, the income will be deducted 0.1 million riels
** the dice is used to assess the availability of off-farm work, e.g. if the result of throwing dice is 5-6, 100% of labor could be sold.

Appendix 14: Co-designing and playing the RADA game

Expert seminar and prototyping process

The co-design process took place in two steps. First, a group of seven experts gathered during a three-day seminar (December 2017) to design prototypes of the game and explore their relevance to address the questions at hand, the quality of their representation of past land use change and their playability by local farmers. The group consisted of two international agronomists including one RPG specialist and one specialist of CA techniques with a good knowledge of the study site, two national agronomists with good CA experience with one of them involved in the CA project, three national socio-economists with two of them involved in the CA project, and a district agricultural extensionist. Together, they reviewed the data generated from previous studies and developed a conceptual model of land use change centered on farmers' decision making and changes in local institutions over the past decades. Different options were explored with different levels of abstraction to find a compromise between the genericity of the model and the level of details that would make it more realistic for players. The RPG was named "RADA" game, an acronym for Resilient Agriculture through co-Design of Agroecology pathways that aimed to capture the essence of the game and the ultimate goal of the expert group.

Testing and refining the game with farmers

Secondly, the RADA game was completely reshuffled through successive learning loops in three villages (Fig. 3). The three co-designed sessions involved the expert team and eight farmers who were selected for their knowledge of historical changes in their villages. Socio-economic factors were also taken into account as each of the four farm types of the farm typology (Appendix 1 and Kong, n.d.) had to be represented by two players. We also tried as much as possible to maintain a gender balance among players by inviting the husband or the wife of the selected households. In the first village, the players were put in a gaming situation with a very limited number of rules and parameters. They had to elicit all the parameters and decide together which values to allocate to each. All elements of the game could be discussed, contested, and revised all along the process. Consequently, in the first village the game co-design took two days, including lengthy discussions between each round about how to improve the game and the collective debriefing at the end of each day. Then, the game was substantially shortened to only one day in the next two villages to avoid player fatigue. The parameters generated in the first village were re-discussed in the second and third villages and were gradually stabilized in order to avoid the lengthy process of parameter elicitation and calibration in the final version of the game. We stopped the design phase after the third village because we could convincingly recreate the historical conditions of land use change in different villages. Compromises had to be found on how to simplify the game so that it would be easily playable by local farmers in about five hours. The co-design team also gradually defined the role of each team member and procedures for facilitation of the player tasks and monitoring of their actions and results during the game and the debriefing sessions after each round and at the end of the game.

Learning loops and stabilization of the game design

At the end of the eight-day co-design period, the expert team developed a workable version of the game including printed posters with all parameters, commonly agreed upon rules, tokens, and the game monitoring sheets. A full sequence of RADA game is shown in Fig. 4, which contains 6 rounds and 87 steps in total. Each round corresponds to a specific period marked by the introduction of a new crop or technique that dramatically influenced LUCC, such as the introduction of hybrid maize in 2006, CA techniques in 2010 or orchards in 2016. The gaming sessions start with a rapid introduction of the facilitation team, the game and its objectives. Farmer-players then introduce themselves and are assigned their initial conditions in the game: family composition and labor force, land area and characteristics, livestock. One facilitator takes care of two players; so there are 4 facilitators for 8 players. They provide explanations to the players without influencing their decisions, compute their risks and rewards, and then report to the whole group the actions and results of the two players at the end of each round. A round consists in five steps: 1) round introduction, 2) game play, 3) risk management, 4) result assessment, and 5) round debrief. The game master provides guidance to the overall game, fixes the pace by introducing each round, and steps with their specific rules and parameters. He collects the monitoring sheets and facilitates the debriefing sessions after each round at the end of the game. These are key moments of expression for the players when they share the reasons for their decisions, the similarities between their situations and actions during the game and in reality, their perception of past and current land use changes. The sixth facilitator is in charge of the game artifacts: bank notes and tokens, dice to represent the risks taken by players (i.e., weather, market, animal disease prevalence…), etc. He also plays the role of external agents of change such as a company introducing a new crop or an extension agent coming with a new technique. CA techniques are introduced at Round 4, for example, and orchard plantations at Round 6.

Gaming sessions

The RADA game was subsequently played in six villages of Rotonak Mondol District in January 2018, all from the same village type, the Upland-Diversified Village (Appendix 1). Three of them were target villages of the CA project while, in the absence of project intervention, the three other villages had only practiced conventional tillage (CT) on upland crops as opposed to CA. In each village, we selected eight household heads (two from each farm type) through stratified sampling from the 95 households who participated in the in-depth interviews. The village authorities were also invited to join the workshop to monitor the game and participate in the debriefing. The gaming session mobilized the players during an entire day, so they received a money compensation corresponding to their agricultural daily wage. In addition, all participants were invited to have lunch together as social interactions that take place around the game also bring very valuable insights.

We recreated the same spatial organization for the RPG in the classroom of each village, in the absence of a public meeting room. The players of the same type sat around a table, apart from each other to avoid mimicking one another, and nearby other farm types to encourage interactions between farm types. The parameters and rules were printed on posters and displayed closed to the game table and the token table (Fig. 5).

Gaming environment and rules

The players were first allocated land, labor and livestock according to their farm type. They were all allocated two main family labor units at the initial stage of their farm as a young couple without children at the time of their installation/migration in the first round. As each family member accounts for 12 man-months, each player receives labor force tokens accordingly to their farm type representing active family members, in which one token equals two man-months. Then, they are allocated an initial number of cells on the 6x6 cells game board, each corresponding to one hectare of land located in the upper part of the topography (green background color) or in the lowland part (yellow background). A few cells are not allocated to any player at the beginning of the game allowing for some agricultural expansion. Among the non-allocated cells, two black cells correspond to stony plots located on hilltops that are generally covered with natural vegetation as they are very difficult to crop. Players are allocated a number of upland and lowland cells proportional to what their farm type manages in reality, according to survey results (see Table 1 for initial land endowment conditions). In addition, some players received livestock (4 cattle heads) depending on their farm type.

The process of farmers' decision-making in the game is illustrated in the UML graph of Fig. 4. The players aim at optimizing farm income with their available resources at the lowest risk possible. The same succession of actions and decisions takes place for each income generating activity, i.e. crop cultivation, livestock raising, collection of natural resources, and off-farm jobs. For example, to decide which crop to cultivate, the player looks at the family labor force available, the land suitability for that crop, the capital to invest (input purchase, seeds, herbicide, fertilizers, or hiring additional labor if family labor force is already saturated), the expected income based on the yield, price of the commodity and risk on yield loss and price fluctuation. Such decisions should be made for each plot owned or rented and also for the two cropping seasons of the year, i.e. dry or wet. The risk is played by throwing dice at the end of each round for the type of climatic year and the market value of agricultural commodities. Then the yield losses or price drops corresponding to the dice number found on the parameter poster are used to compute the results of the round for all players (Appendix 3). Once the results are announced by the facilitators, the players are offered to invest their surpluses, if any, in purchasing, renting or selling farm assets, including livestock, land, labor force (e.g. through off-farm activities or out-migration), equipment (e.g. power tiller) and services (e.g. for land preparation or sowing) or to get into debt with banks or microfinance services in case of negative results. Potential surpluses are computed by removing the basic family consumption needs from the net margin of yearly farm and off-farm activities.

At each round, income-generating activities proposed to the players change according to what happened in reality (e.g. introduction of maize, cassava, and then orchards). Also, the value of 'family consumption needs' gradually increases round after round to reflect the rapid increase in cost of living observed during the field surveys (see parameter in Appendix 3). Consequently, the amount of money generated by each player has to increase all along the game to sustain their livelihoods and generate surpluses for further investments. The risk level associated with high return commodities, such as orchards also tends to increase round after round as farmers use more inputs and become more vulnerable to economic losses. Beside new crops, new cropping practices were introduced at the beginning of each round either at the initiative of the players or suggested by the facilitators as market driven (e.g. herbicide, fertilizers, power tiller) or extension driven (e.g. cover crops, no-till planter) innovations. The introduction of CA techniques at the beginning of Round 4 coincided with land saturation by maize and decreasing yields and profits. The facilitators projected video clips and photos to promote CA practices, including experiences and testimonies from farmers from the CA villages within the district. The technicians spent as much as time as needed to discuss and answer all the questions from participants, especially in CT (i.e. non-CA) villages.

References

Abrami, G., Vejpas, C., Bousquet, F., Trebuil, G., 2010. Participatory modelling and simulation of the rice seed system in Northeast Thailand, in: ISDA 2010. Cirad-Inra-SupAgro, p. 27.

ADB, 2001. Report and recommendation of the president to the board of directors on a proposed loan to the kingdom of Cambodia for the northwestern rural development project. Asian Development Bank, Phnom Penh.

Alagappa, M., 1995. Political Legitimacy in Southeast Asia: The Quest for Moral Authority, Bruce M.Koppel. Stanford University Press.

Alvarez, S., Paas, W., Descheemaeker, K., Tittonell, P.A., Groot, J.C.J., 2014. Typology construction, a way of dealing with farm diversity: General guidelines for Humidtropics.

Alvarez, S., Timler, C.J., Michalscheck, M., Paas, W., Descheemaeker, K., Tittonell, P., Andersson, J.A., Groot, J.C.J., 2018. Capturing farm diversity with hypothesis-based typologies: An innovative methodological framework for farming system typology development. PLoS One 13, e0194757.

Arensen, L.J., 2012. Displacement, Diminishment, and Ongoing Presence. Asian Enthology 71, 159–178.

Arruda, L., Beneduzi, A., Martins, A., Lisboa, B., Lopes, C., Bertolo, F., Passaglia, L.M.P., Vargas, L.K., 2013. Screening of rhizobacteria isolated from maize (Zea mays L.) in Rio Grande do Sul State (South Brazil) and analysis of their potential to improve plant growth. Appl. Soil Ecol. https://doi.org/10.1016/j.apsoil.2012.09.001

Baird, I.G., 2011. Turning Land into Capital, Turning People into Labour: Primitive Accumulation and the Arrival of Large-Scale Economic Land Concessions in the Lao People's Democratic Republic, New Proposals: Journal of Marxism and Interdisciplinary Inquiry.

Barnaud, C., Bousquet, F., Trebuil, G., 2008. Multi-agent simulations to explore rules for rural credit in a highland farming community of Northern Thailand. Ecol. Econ. 66, 615–627. https://doi.org/10.1016/j.ecolecon.2007.10.022

Barral, S., Touzard, I., Ferraton, N., Rasse-Mercat, E., Pillot, D., 2011. Assessing smallholder farming. Diagnostic analysis of family-based agricultural systems in a small region. Editions du SEARCA.

Barreteau, O., Bots, P., Daniell, K., Etienne, M., Perez, P., Barnaud, C., Bazile, D., Becu, N., Castella, J.J.-C., Daré, W., Trebuil, G., Perez, P., Trebuil, G., Castella, J.J.-C., Dare, W., 2013. Participatory approaches, in: Understanding Complex Systems, Understanding Complex Systems. Springer Berlin Heidelberg, Heidelberg, Allemagne, pp. 197–234.

Begum, I., Alam, M., Rahman, S., Van Huylenbroeck, G., 2014. An assessment of the contract farming system in improving market access for smallholder poultry farmers in Bangladesh, in: Silva, C.A. da, Rankin, M. (Eds.), Contract Farming for Inclusive Market Access. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, pp. 39–56.

Belfield, S.C., Martin, R.J., Scott, J.F., 2013. Alternative cropping systems for north-west Cambodia. Int. J. Environ. Rural Dev. 4, 209–214.

Bernstein, H., 1996. Agrarian questions then and now. J. Peasant Stud. 24, 22–59. https://doi.org/10.1080/03066159608438630

Bernstein, H., 1977. Notes on capital and peasantry. Rev. Afr. Polit. Econ. 4, 60–73. https://doi.org/10.1080/03056247708703339

Berre, D., Baudron, F., Kassie, M., Craufurd, P., Lopez-Ridaura, S., 2016. Different ways to cut a cake: comparing expert-based and statistical typologies to target sustainable intensification technologies, a case-study in Southern Ethiopia. Exp. Agric. 1–17. https://doi.org/DOI: 10.1017/S0014479716000727

Berthet, E.T., Hickey, G.M., 2018. Organizing collective innovation in support of sustainable agro-ecosystems: The role of network management. Agric. Syst. 165, 44–54. https://doi.org/https://doi.org/10.1016/j.agsy.2018.05.016

Bertrand, R., 2011. Agrarian diagnosis and characterization of farming systems in two villages in Battambang province (Cambodia) with the set up of a farming systems reference monitoring network. Montpellier SupAgro, Montpellier.

Birachi, E., van Rooyen, A., Some, H., Maute, F., Cadilhon, J., Adekunle, A.A., Swaans, K., 2013. Innovation platforms for agricultural value chain development. Innov. platforms Pract. Br. 1–4. https://doi.org/10.4324/9781315646817 M4 - Citavi

Botta, A., Jankowski, F., Diao Camara, A., Corniaux, C., 2017. Using forum theatre to debate synergies and trade-offs between adaptation strategies of pastoral society with scientists, local and national stakeholders. Resil. 2017.

Boulakia, S., Chabierski, S., San, S., Kou, P., Leng, V., Chhit, K., Sar, V., Thy, T., Som, L., 2010. Annual activity report 2007-2009. Phnom Penh, Cambodia.

Boulakia, S., Kong, R., Eberle, M., 2013. Sustainable farming to sustain Cambodia’s future. Phnom Penh.

Brunet, R., 1980. La composition des modèles dans l ’ analyse spatiale. Espac. géographique 9, 253–265. https://doi.org/10.3406/spgeo.1980.3572

Bruun, T.B., de Neergaard, A., Burup, M.L., Hepp, C.M., Larsen, M.N., Abel, C., Aumtong, S., Magid, J., Mertz, O., 2017. Intensification of Upland Agriculture in Thailand: Development or Degradation? L. Degrad. Dev. 28, 83–94. https://doi.org/10.1002/ldr.2596

Byres, T.J., 1977. Agrarian transition and the Agrarian question. J. Peasant Stud. 4, 258–274. https://doi.org/10.1080/03066157708438024

Campbell, B.M., Thornton, P., Zougmoré, R., van Asten, P., Lipper, L., 2014. Sustainable intensification: What is its role in climate smart agriculture? Curr. Opin. Environ. Sustain. 8, 39–43. https://doi.org/10.1016/J.COSUST.2014.07.002

Castella, J.-C., 2012. Agrarian transition and farming system dynamics in the uplands of South-East Asia, in Hauswirth et Al (Eds) Conservation Agriculture and Sustainable Upland Livelihoods. Innovations for, with and by Farmers to Adapt to Local and Global Changes—Proceedings of the 3rd International Conference on Conservation Agriculture in Southeast Asia. CIRAD, Montpellier; NOMAFSI, Phu Tho; University of Queensland, Brisbane, Hanoi, Vietnam, pp. 4–21.

Castella, J.-C., Jobard, E., Lestrelin, G., Nanthavong, K., Lienhard, P., 2012. Maize expansion in Xieng Khouang province, Laos: what prospects for conservation agriculture?, in: The 3rd International Conference. p. 300.

Castella, J.-C., Ornetsmüller, C., Lestrelin, G., Verburg, P., Lienhard, P., 2016. Mitigating the negative impacts of the maize boom on landscapes and livelihoods in Laos, in: International Conference on Agri-Chains and Sustainable Development: Linking Local and Global Dynamics. CIRAD, Montpellier, France, pp. 10–12.

Christiaensen, L., 2009. Revisiting the global food architecture: Lessons from the 2008 food crisis. The United Nations University World Institute for Development Economics Research (UNU-WIDER), Helsinki.

Christiansen, G., Simmoneaux, J., Hazard, L., 2018. Agroecological transition : human skills and social life matter for local actors. 13th Eur. IFSA Symp. 1-5 July 2018, Chania 16.

Cochet, H., 2015. Comparative Agriculture. Springer Netherlands.

Cramb, R., Manivong, V., Newby, J.C., Sothorn, K., Sibat, P.S., 2017. Alternatives to land grabbing: exploring conditions for smallholder inclusion in agricultural commodity chains in Southeast Asia. J. Peasant Stud. 44, 813–841. https://doi.org/10.1080/03066150.2016.1242482

Cramb, R.A., Colfer, C.J.P., Dressler, W., Laungaramsri, P., Le, Q.T., Mulyoutami, E., Peluso, N.L., Wadley, R.L., 2009. Swidden Transformations and Rural Livelihoods in Southeast Asia. Hum. Ecol. 37, 323–346. https://doi.org/10.1007/s10745-009-9241-6

Cristofaro, M., 2017. Herbert Simon's bounded rationality. J. Manag. Hist. 23, 170–190. https://doi.org/10.1108/JMH-11-2016-0060

Crocker, C.D., 1962. The general soil map of the kingdom of Cambodia and the exploratory survey of soils of Cambodia. Royal Cambodian Government Soil Commission/USAID, Phnom Penh.

Davis, K.F., Yu, K., Rulli, M.C., Pichdara, L., D'Odorico, P., 2015. Accelerated deforestation driven by large-scale land acquisitions in Cambodia. Nat. Geosci. 8, 772. https://doi.org/10.1038/ngeo2540

De Koninck, R., 2011. Agrarian Transition, in: Lagrée, S. (Ed.), Transitions Decreed, Transitions Experienced. From Global to Local: Methodological, Cross-Cutting and Critical Approaches. Tam Đảo Summer School Week 2010. AFD, Tam Dao, Vietnam, pp. 44–57.

Diepart, J.-C., Ngin, C., Vongphaisit, C., U, S.T., Nguyễn, A.P., 2017. Large-Scale Land Acquisition for Agricultural Development in the Mekong Region (CLMV): An Update, in: Regional Workshop on Responsible Large Scale Agricultural Investment in the Mekong. MRLG, Ipsard, and OXFAM, Vientiane, Laos PDR.

Diepart, J., Sem, T., 2015. The Cambodian peasantry and the formalisation of land rights: historical overview and current issues. Groupe de Recherches Asie de l'Est et du Sud Est (GRAESE), Liège.

Diepart, J.C., 2015. The fragmentation of land tenure ystems in Cambodia: peasants and the formalization of land rights, Country Profile: Cambodia. Foncièr et Développement, Paris, France.

Diepart, J.C., Dupuis, D., 2014. The peasants in turmoil: Khmer Rouge, state formation and the control of land in northwest Cambodia. J. Peasant Stud. 41, 445–468. https://doi.org/10.1080/03066150.2014.919265

Diepart, J.C., Sem, T., 2018. Fragmented Territories: Incomplete Enclosures and Agrarian Change on the Agricultural Frontier of Samlaut District, North-West Cambodia. J. Agrar. Chang. 18, 156–177. https://doi.org/10.1111/joac.12155

Dixon, J., 2019. Concept and Classifications of Farming Systems, in: Ferranti, P., Berry, E.M., Anderson, J.R.B.T.-E. of F.S. and S. (Eds.), . Elsevier, Oxford, pp. 71–80. https://doi.org/https://doi.org/10.1016/B978-0-08-100596-5.22155-0

Dixon, J., 2018a. Re-introduction of Sustainability into Agricultural and Rural Systems Development, in: Agroecology Futures Regional Forum. GRET/CIRAD/MAFF, Siem Reap, Cambodia.

Dixon, J., 2018b. Concept and Classifications of Farming Systems, Encyclopedia of Food Security and Sustainability. Elsevier. https://doi.org/10.1016/b978-0-08-100596-5.22155-0

Dixon, J.A., Gibbon, D.P., Gulliver, A., 2001. Farming systems and poverty : improving farmers' livelihoods in a changing world. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Doch, S., Diepart, J.-C., Heng, C., 2015. A multi-scale flood vulnerability assessment of agricultural production in the context of environmental change: The case of the Sangkae River watershed, Battambang province, in: Diepart, J.-C. (Ed.), Learning for Resilience: Insights from Cambodia's Rural Communities. The Learning Institute, Phnom Penh, pp. 19–49.

Dressler, W.H., Wilson, D., Clendenning, J., Cramb, R., Keenan, R., Mahanty, S., Bruun, T.B., Mertz, O., Lasco, R.D., 2017. The impact of swidden decline on livelihoods and ecosystem services in Southeast Asia: A review of the evidence from 1990 to 2015. Ambio 46, 291–310. https://doi.org/10.1007/s13280-016-0836-z

Etienne, M., 2014. Companion Modelling: A Participatory Approach to Support Sustainable Development. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-94-017-8557-0

Falconnier, G.N., Descheemaeker, K., Mourik, T.A. Van, Sanogo, O.M., Giller, K.E., 2015. Understanding farm trajectories and development pathways : Two decades of change in southern Mali. AGSY 139, 210–222. https://doi.org/10.1016/j.agsy.2015.07.005

FAO, 2018. The 10 elements of agroecology. Guiding the transition to sustainable food and agricultural systems. Fao 15.

Fella, T., Barua, S., Tamminen, L., Hatcher, J., 2017. Systematic and Rapid Assessment of Concessions Using GIS and Remote Sensing: The Case of Economic Land Concessions in Cambodia, in: Responsible Land Governance: Towards an Evidence Based Approach. Annual World Bank Conference on Land and Poverty. World Bank, Washington DC.

Flor, R.J., Leeuwis, C., Maat, H., Gummert, M., 2016. Rice postharvest learning alliance in Cambodia: comparison of assumptions and implementation of a network approach. J. Dev. Eff. 8, 489–507. https://doi.org/10.1080/19439342.2016.1231705

Forestry Administration, 2010. Cambodia forestry outlook study, Working Paper No. APFSOS II/ WP/ 2010/ 32. Food and Agriculture Organization of the United Nations, Bangkok.

French, L., 2002. From Politics to Economics at the Thai–Cambodian Border: Plus Ça Change. Int. J. Polit. Cult. Soc. 15, 427–470. https://doi.org/10.1023/a:1014028510016

Fresco, L.O., Westphal, E., 1988. A Hierarchical Classification of Farm Systems. Exp. Agric. 24, 399–419. https://doi.org/DOI: 10.1017/S0014479700100146

Friis, C., Nielsen, J.Ø., 2014. Exploring the potential of the telecoupling framework for understanding land change, THESys Discussion Paper No. 2014-1. Berlin.

Gao, B., 1996. NDWI—A normalized difference water index for remote sensing of vegetation liquid water from space. Remote Sens. Environ. 58, 257–266. https://doi.org/10.1016/S0034-4257(96)00067-3

Geiger, D., 2008. Turner in the Tropics: The Frontier Concept Revisited. Front. Encount. Indig. Communities Settlers Asia Lat. Am. 75–216.

Geist, H., McConnell, W., Lambin, E.F., Moran, E., Alves, D., Rudel, T., 2006. Causes and trajectories of land-use/cover change. Land-use land-cover Chang. 41–70.

Geist, H.J., Lambin, E.F., 2002. Proximate Causes and Underlying Driving Forces of Tropical Deforestation: Tropical forests are disappearing as the result of many pressures, both local and regional, acting in various combinations in different geographical locations. Bioscience 52, 143–150. https://doi.org/10.1641/0006-3568(2002)052[0143:PCAUDF]2.0.CO;2

Gilbert, C.L., Morgan, C.W., 2010. Food price volatility. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 365, 3023–34. https://doi.org/10.1098/rstb.2010.0139

Giller, K.E., Tittonell, P., Rufino, M.C., van Wijk, M.T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R., Corbeels, M., Rowe, E.C., Baijukya, F., Mwijage, A., Smith, J., Yeboah, E., van der Burg, W.J., Sanogo, O.M., Misiko, M., de Ridder, N., Karanja, S., Kaizzi, C., K'ungu, J., Mwale, M., Nwaga, D., Pacini, C., Vanlauwe, B., 2011. Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. Agric. Syst. 104, 191–203. https://doi.org/https://doi.org/10.1016/j.agsy.2010.07.002

Hall, D., 2011. Land grabs, land control, and Southeast Asian crop booms. J. Peasant Stud. 38, 837–

857. https://doi.org/10.1080/03066150.2011.607706

Hameiri, S., 2010. State Building, Patronage and the Anti-Pluralist Politics of Stability in Cambodia, in: Regulating Statehood: State Building and the Transformation of the Global Order. Palgrave Macmillan UK, London, pp. 177–207. https://doi.org/10.1057/9780230282001_8

Hansen, M.C., Potapov, P. V, Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S. V, Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G., 2013. High-Resolution Global Maps of 21st-Century Forest Cover Change. Science (80-.). 342, 850–853. https://doi.org/10.1126/science.1244693

Haralick, R.M., Shanmugam, K., Dinstein, I., 1973. Textural Features for Image Classification. IEEE Trans. Syst. Man. Cybern. SMC-3, 610–621. https://doi.org/10.1109/TSMC.1973.4309314

Hettig, E., Lay, J., Sipangule, K., 2016. Drivers of Households' Land-Use Decisions: A Critical Review of Micro-Level Studies in Tropical Regions. Land 5, 32.

Hirsch, P., 1995. Thailand and the new geopolitics of Southeast Asia: Resource and environmental issues, in: Rigg, J. (Ed.), Counting the Costs: Economic Growth and Environmental Change in Thailand. Institute of Southeast Asian Studies, Singapore, pp. 235–259.

Howeler, R.H., Cadavid, L.F., Burckhardt, E., 1982. Response of cassava to VA mycorrhizal inoculation and phosphorus application in greenhouse and field experiments. Plant Soil 69, 327–339. https://doi.org/10.1007/BF02372454

Hughes, C., 2003. The Political Economy of Cambodia's Transition, 1991-2001. RoutledgeCurzon.

Hun, S., 2006. Closing speech delivered at the Open Academic Forum Commemorating the Fifteen Anniversary of the Political Settlement on the Cambodian Conflict.

Hurni, K., Schneider, A., Heinimann, A., Nong, D.H., Fox, J., 2017. Mapping the Expansion of Boom Crops in Mainland Southeast Asia Using Dense Time Stacks of Landsat Data. https://doi.org/10.3390/rs9040320

Husson, O., Tran Quoc, H., Boulakia, S., Chabanne, A., Tivet, F., Bouzinac, S., Lienhard, P., Michellon, R., Chabierski, S., Boyer, J., Enjalric, F., Rakotondramanana, Moussa, N., Jullien, F., Balarabe, O., Rattanatray, B., Castella, J., Charpentier, H., Séguy, L., 2016. Co-designing innovative cropping systems that match biophysical and socio-economic diversity: The DATE approach to Conservation Agriculture in Madagascar, Lao PDR and Cambodia. Renew. Agric. Food Syst. 31, 452–470. https://doi.org/10.1017/S174217051500037X

Hyman, J., Bailis, R., 2018. Assessment of the Cambodian National Biodigester Program. Energy Sustain. Dev. 46, 11–22. https://doi.org/https://doi.org/10.1016/j.esd.2018.06.008

Ingalls, M.L., Diepart, J.-C., Truong, N., Hayward, D., Neil, T., Phomphakdy, C., Bernhard, R., Fogarizzu, S., Epprecht, M., Nanhthavong, V., Vo, D.H., Nguyen, D., Nguyen, P.A., Saphangthong, T., Inthavong, C., Hett, C., Tagliarino, N., 2018a. State of Land in the Mekong Region. Centre for Development and Environment, University of Bern and Mekong Region Land Governance, Bern, Switzerland and Vientiane, Lao PDR, with Bern Open Publishing.

Ingalls, M.L., Diepart, J.-C., Truong, N., Hayward, D., Niel, T., Sem, T., Phomphakdy, M., Bernhard, R., Fogarizzu, S., Epprecht, M., Nanthavong, V., Vo, D.H., Nguyen, D., Nguyen, P.A., Saphanthong, T., Inthavong, C., Hett, C., Tagliarino, N., 2018b. The Mekong State of Land.

Inter-agency Report, 2011. Price Volatility in Food and Agricultural Markets: Policy Responses.

Jepsen, R.M., Palm, M., Bruun, B.T., 2019. What Awaits Myanmar's Uplands Farmers? Lessons Learned from Mainland Southeast Asia. L. . https://doi.org/10.3390/land8020029

Jiao, X., Pouliot, M., Walelign, S.Z., 2017. Livelihood Strategies and Dynamics in Rural Cambodia. World Dev. 97, 266–278. https://doi.org/10.1016/J.WORLDDEV.2017.04.019

Kassam, A., Friedrich, T., 2012. An ecologically sustainable approach to agricultural production intensification : Global perspectives and developments An ecologically sustainable approach to agricultural p - roduction intensification : Global perspectives and developments 1. F. Actions Sci. Reports 1, 1–7.

Kassam, A., Friedrich, T., Derpsch, R., 2018. Global spread of Conservation Agriculture. Int. J. Environ. Stud. 00, 1–23. https://doi.org/10.1080/00207233.2018.1494927

Keil, A., Saint-Macary, C., Zeller, M., 2008. Maize boom in the uplands of Northern Vietnam: economic importance and environmental implications, Discussion Paper No. 4/2008. Universität Hohenheim, Stuttgart.

Kelly, P.F., 2011. Migration, agrarian transition, and rural change in Southeast Asia. Crit. Asian Stud. 43, 479–506. https://doi.org/10.1080/14672715.2011.623516

Kem, S., 2017. Commercialisation of Smallholder Agriculture in Cambodia: Impact of the Cassava Boom on Rural Livelihoods and Agrarian Change. The University of Queensland, Brisbane.

Köbrich, C., Rehman, T., Khan, M., 2003. Typification of farming systems for constructing representative farm models: two illustrations of the application of multi-variate analyses in Chile and Pakistan. Agric. Syst. 76, 141–157. https://doi.org/https://doi.org/10.1016/S0308-521X(02)00013-6

Kong, R., n.d. Characterizing the diversity of upland farming systems and their capacity to innovate in the northwestern uplands of Cambodia. Agric. Ecosyst. Environ. Submitted.

Kong, R., Castella, Jean-Christophe Tivet, F., Diepart, J.-C., Leng, V., Suos, V., Pat, S., Sen, R., n.d. Investigating farmer's decision-making in relation with the adoption of conservation agriculture in the northwestern uplands of Cambodia. Ecol. Soc. under review.

Kong, R., Diepart, J.-C., Castella, J.-C., Lestrelin, G., Tivet, F., Belmain, E., Bégué, A., 2019. Understanding the drivers of deforestation and agricultural transformations in the Northwestern uplands of Cambodia. Appl. Geogr. 102, 84–98. https://doi.org/10.1016/J.APGEOG.2018.12.006

Kong, R., Sar, V., Leng, V., Trang, S., Boulakia, S., Tivet, F., Seguy, L., 2016. Conservation Agriculture for Climate-Resilient Rain-Fed Uplands in the Western Regions of Cambodia: Challenges, Opportunities, and Lessons from a 10-Year R&D Program, in: Sajise, P.E., Cadiz, M.C.H., Bantayan, B.R. (Eds.), Learning and Coping with Change: Case Stories of Climate Change Adaptation in Southeast Asia. The Southeast Asian Regional Center for Graduate Study and Research in Agriculture (SEARCA), Los Baños, pp. 55–81.

Kong, R., Sar, V., Leng, V., Trang, S., Boulakia, S., Tivet, F., Seguy, L., 2016. Conservation Agriculture for Climate-Resilient Rain-Fed Uplands in the Western Regions of Cambodia: Challenges, Opportunities, and Lessons from a 10-Year R&D Program, in: Sajise, P.E., Cadiz, M.C.H., Bantayan, B.R. (Eds.), Learning and Coping with Change: Case Stories of Climate Change Adaptation in Southeast Asia. The Southeast Asian Regional Center for Graduate Study and Research in Agriculture (SEARCA), Los Baños, Philippines, Philippines, pp. 55–81.

Kuivanen, K.S., Alvarez, S., Michalscheck, M., Adjei-Nsiah, S., Descheemaeker, K., Mellon-Bedi, S., Groot, J.C.J., 2016a. Characterising the diversity of smallholder farming systems and their constraints and opportunities for innovation: A case study from the Northern Region, Ghana. NJAS - Wageningen J. Life Sci. 78, 153–166. https://doi.org/http://dx.doi.org/10.1016/j.njas.2016.04.003

Kuivanen, K.S., Michalscheck, M., Descheemaeker, K., Adjei-Nsiah, S., Mellon-Bedi, S., Groot, J.C.J., Alvarez, S., 2016b. A comparison of statistical and participatory clustering of smallholder farming systems – A case study in Northern Ghana. J. Rural Stud. 45, 184–198. https://doi.org/http://dx.doi.org/10.1016/j.jrurstud.2016.03.015

Kull, C.A., Kueffer, C., Richardson, D.M., Vaz, A.S., Vicente, J.R., Honrado, J.P., 2018. Using the "regime shift" concept in addressing social-ecological change. Geogr. Res. 56, 26–41. https://doi.org/10.1111/1745-5871.12267

Kyomugisha, H., Sebatta, C., Mugisha, J., 2018. Potato market access, marketing efficiency and on-farm value addition in Uganda. Sci. African 1, e00013. https://doi.org/10.1016/j.sciaf.2018.e00013

Lambin, E.F., Geist, H.J., Lepers, E., 2003. Dynamics of Land-Use and Land-Cover Change in Tropical Regions. Annu. Rev. Environ. Resour. 28, 205–241. https://doi.org/10.1146/annurev.energy.28.050302.105459

Lambin, E.F., Turner, B.L., Geist, H.J., Agbola, S.B., Angelsen, A., Bruce, J.W., Coomes, O.T., Dirzo, R., Fischer, G., Folke, C., George, P.S., Homewood, K., Imbernon, J., Leemans, R., Li, X., Moran, E.F., Mortimore, M., Ramakrishnan, P.S., Richards, J.F., Skånes, H., Steffen, W., Stone, G.D., Svedin, U., Veldkamp, T.A., Vogel, C., Xu, J., 2001. The causes of land-use and land-cover change: moving beyond the myths. Glob. Environ. Chang. 11, 261–269. https://doi.org/10.1016/S0959-3780(01)00007-3

Landais, E., 1998. Modelling farm diversity: new approaches to typology building in France. Agric. Syst. 58, 505–527. https://doi.org/10.1016/S0308-521X(98)00065-1

Laurent, C., van Rooyen, C.J., Madikizela, P., Bonnal, P., Carstens, J., 1999. Household typology for relating social diversity and technical change. Agrekon 38, 190–208. https://doi.org/10.1080/03031853.1999.9524914

Le Billon, P., 2002. Logging in Muddy Waters: The Politics of Forest Exploitation in Cambodia. Crit. Asian Stud. 34, 563–586. https://doi.org/10.1080/1467271022000035938

Le Billon, P., 2000. The Political Ecology of Transition in Cambodia 1989–1999: War, Peace and Forest Exploitation. Dev. Change 31, 785–805. https://doi.org/10.1111/1467-7660.00177

Le Billon, P., 1999. Power is consuming the forest: the political ecology of conflict and reconstruction in Cambodia. University of Oxford.

Le Billon, P., Springer, S., 2007. Between war and peace: Violence and accommodation in the Cambodian logging sector, in: Jong, W. De, Donovan, D., Abe, K.-I. (Eds.), Extreme Conflict and Tropical Forests. Springer Netherlands, Dordrecht, pp. 17–36. https://doi.org/10.1007/978-1-4020-5462-4_2

Leakey, R.R.B., 2017. Chapter 2 - The Role of Trees in Agroecology and Sustainable Agriculture in the Tropics: This chapter was previously published in Leakey, R.R.B., 2014. Annual Review of Phytopathology 52, 113–133, with permission of Annual Reviews, in: Leakey, R.R.B.B.T.-M.A. (Ed.), . Academic Press, pp. 7–18. https://doi.org/https://doi.org/10.1016/B978-0-12-805356-0.00002-7

Lechervy, C., 1996. L'économie des guerres cambodgiennes: accumulation et dispersion, in: Ean, F., Rufin, J.-C. (Eds.), Economie Des Guerres Civiles. Hachette, Paris, pp. 189–232.

Lestrelin, G., Castella, J.-C., Kong, R., Venot, J.-P., Neang, M., Lienhard, P., Tivet, F., 2019. Exploring adaptation pathways to global change: lessons from failed attempts to bring agroecology to scale in Southeast Asia, in: Fourth Open Science Meeting of the Global Land Programme (GLP 4th OSM 2019), 24-26 April 2019. Bern, Switzerland.

LICADHO, 2011. Road database.

Lopez Ridaura, S., Tittonell, P., 2011. Coping with heterogeneity. Typologies for agricultural research and development, in: 5th World Congress on Conservation Agriculture & 3rd Farming Systems Design Conference. Brisbane, Australie.

Ly, P., Jensen, L.S., Bruun, T.B., Rutz, D., de Neergaard, A., 2012. The System of Rice Intensification: Adapted practices, reported outcomes and their relevance in Cambodia. Agric. Syst. 113, 16–27. https://doi.org/https://doi.org/10.1016/j.agsy.2012.07.005

Macours, K., Swinnen, J.F.M., 2002. Patterns of Agrarian Transition. Econ. Dev. Cult. Change 50, 365–394. https://doi.org/10.1086/322883

MAFF, 2015. Annual report 2015-2016. Ministry of Agriculture Forestry and Fisheries (MAFF), Phnom Penh.

MAFF, 2001. Annual report 2001-2002. Ministry of Agriculture Forestry and Fisheries (MAFF), Phnom Penh.

Mahanty, S., Milne, S., 2016. Anatomy of a boom: Cassava as a ‘gateway’ crop in Cambodia’s north eastern borderland. Asia Pac. Viewp. 57, 180–193. https://doi.org/10.1111/apv.12122

Maikhuri, R.K., Semwal, R.L., Rao, K.S., Saxena, K.G., 1997. Agroforestry for rehabilitation of degraded community lands: A case study in the Garhwal Himalaya, India. Int. Tree Crop. J. 9, 91–101. https://doi.org/10.1080/01435698.1997.9752964

Malanson, G.P., Verdery, A.M., Walsh, S.J., Sawangdee, Y., Heumann, B.W., McDaniel, P.M., Frizzelle, B.G., Williams, N.E., Yao, X., Entwisle, B., Rindfuss, R.R., 2014. Changing crops in response to climate: virtual Nang Rong, Thailand in an agent based simulation. Appl. Geogr. 53, 202–212. https://doi.org/10.1016/j.apgeog.2014.06.010

Martin, B., Farquharson, B., Spriggs, J., Fitzgerald, R., Scott, F., El, S., Touch, V., Keo, K., 2013. Enhancing production and marketing of maize and soybean in north-western Cambodia and production of summer crops in north-eastern Australia. Australian Centre for International Agricultural Research (ACIAR), Canberra.

McKenney, B., Prom, T., 2002. Natural resources and rural livelihoods in Cambodia: A baseline assessment, Working paper 23. Cambodia Development Resource Institute (CDRI), Phnom Penh.

Mekong Secretariat & River Commission, 1994. Cambodia Land Cover Atlas (1985/87 to 1992/1993). Food and Agriculture Organization of the United Nations (FAO) and United Nations Development Programme (UNDP), Phnom Penh.

Meyfroidt, P., Carlson, K.M., Fagan, M.E., Gutiérrez-Vélez, V.H., Macedo, M.N., Curran, L.M., Defries, R.S., Dyer, G.A., Gibbs, H.K., Lambin, E.F., Morton, D.C., Robiglio, V., 2014. Multiple pathways of commodity crop expansion in tropical forest landscapes. Environ. Res. Lett. 9. https://doi.org/10.1088/1748-9326/9/7/074012

Milestad, R., Dedieu, B., Darnhofer, I., Bellon, S., 2012. Farms and farmers facing change: The adaptive approach, in: Farming Systems Research into the 21st Century: The New Dynamic. pp. 365–385. https://doi.org/10.1007/978-94-007-4503-2

Mishra, A., Whitten, M., Ketelaar, J.W., Salokhe, V.M., 2006. The System of Rice Intensification (SRI): a challenge for science, and an opportunity for farmer empowerment towards sustainable agriculture. Int. J. Agric. Sustain. 4, 193–212. https://doi.org/10.1080/14735903.2006.9684802

MLMUPC, 2005. Road database.

Montgomery, S.C., Martin, R.J., Guppy, C., Wright, G.C., Tighe, M.K., 2017. Farmer knowledge and perception of production constraints in Northwest Cambodia. J. Rural Stud. 56, 12–20. https://doi.org/10.1016/j.jrurstud.2017.09.003

MPWT, JICA, 2003. Cambodia Reconnaissance Survey Digital Data.

Müller, D., Sun, Z., Vongvisouk, T., Pflugmacher, D., Xu, J., Mertz, O., 2014. Regime shifts limit the predictability of land-system change. Glob. Environ. Chang. 28, 75–83. https://doi.org/10.1016/j.gloenvcha.2014.06.003

NCDD, 2010. Commune Database Online. 2005-2010.

Nesbitt, H.J., 1997. Rice production in Cambodia. International Rice Research Institute (IRRI), Manila, the Philippines.

Nguyen, T.T., Do, T.L., Bühler, D., Hartje, R., Grote, U., 2015. Rural livelihoods and environmental resource dependence in Cambodia. Ecol. Econ. 120, 282–295. https://doi.org/10.1016/J.ECOLECON.2015.11.001

NIS, 2009. Cambodian Demographic Census 2008. National Institute of Statistics (NIS), Phnom Penh.

Ornetsmüller, C., Castella, J.C., Verburg, P.H., 2018. A multiscale gaming approach to understand farmer's decision making in the boom of maize cultivation in Laos. Ecol. Soc. 23. https://doi.org/10.5751/ES-10104-230235

Pacini, G.C., Colucci, D., Baudron, F., Righi, E., Corbeels, M., Tittonell, P., Stefanini, F.M., 2013. Combining multi-dimensional scaling and cluster analysis to describe the diversity of rural households. Exp. Agric. 50, 376–397. https://doi.org/10.1017/S0014479713000495

PDLMUPC, 2014. Update of road database 2014.

PDP-BB, 2015. Commune database 2011-2015.

PDP-PL, 2015. Commune database 2011-2015.

Perrotton, A., de Garine-Wichatitsky, M., Valls-Fox, H., Le Page, C., 2017. My cattle and your park: codesigning a role-playing game with rural communities to promote multistakeholder dialogue at the edge of protected areas. Ecol. Soc. 22. https://doi.org/10.5751/ES-08962-220135

Phaipasith, S., 2016. Study on the Impacts of Feeder Road Expansion on Livelihood in Natong Cluster, Huaphan Province, Lao PDR. Hohai University, Nanjing, China.

Pilgrim, J., Ngin, C., Diepart, J.-C., 2012. Multiple migrations, displacements and land transfers at Ta Kream in Northwest Cambodia, in: Hecht, S.B., Kandel, S., Morales, A. (Eds.), Migration, Rural Livelihoods and Natural Resource Management. International Development Research Centre (IDRC) of Canada - Ford Foundation - Fundación PRISMA, El Salvador, pp. 33–56.

Pretty, J., 2018. Intensification for redesigned and sustainable agricultural systems. Science (80-.). 362, eaav0294. https://doi.org/10.1126/science.aav0294

Rezitis, A.N., Ntinou, A.G., Pachis, D.N., 2015. Investigating the international prices of wheat and rice. Agric. Food Econ. 3, 16. https://doi.org/10.1186/s40100-015-0035-4

Riethmüller, R., 1988. Differentiation and dynamics of land-use systems in a mountain-valley environment: a case study of new colonization areas in the upper Mae Nam Pa Sak catchment area, Thailand, in: Manshard, W., Morgan, W. (Eds.), Agricultural Expansion and Pioneer Settlements in the Humid Tropics. The United Nations University, Tokyo, pp. 74–94.

Robles, M., Torero, M., Braun, J. von, 2009. When speculation matter, Teaching Statistics. International Food Policy Research Institute (IFPRI), Washington DC, USA.

Rodrigues, A.S.L., Ewers, R.M., Parry, L., Souza, C., Veríssimo, A., Balmford, A., 2009. Boom-and-Bust Development Patterns Across the Amazon Deforestation Frontier. Science (80-.). 324, 1435–1437. https://doi.org/10.1126/science.1174002

Rouse, J. W., J., Haas, R.H., Schell, J.A., Deering, D.W., 1974. Monitoring vegetation systems in the Great Plains with ERTS, in: Proceedings of the Third ERTS Symposium. NASA SP-351 I, pp. 309–317.

Rowcroft, P., 2008. Frontiers of Change: The Reasons Behind Land-use Change in the Mekong Basin. AMBIO A J. Hum. Environ. 37, 213–218. https://doi.org/10.1579/0044-7447(2008)37[213:FOCTRB]2.0.CO;2

Royal Government of Cambodia, 1993. Royal Decree on the Protection of Natural Areas, PRK/1Nov93. Phnom Penh, Cambodia.

Ruben, R., Pender, J., 2004. Rural diversity and heterogeneity in less-favoured areas: the quest for policy targeting. Food Policy 29, 303–320. https://doi.org/10.1016/J.FOODPOL.2004.07.004

Rubiano, J.E., 2001. Farmers' decision making on land use—the importance of soil conditions in the case of Río Cabuyal watershed, Colombia AU - Ravnborg, Helle Munk. Geogr. Tidsskr. J. Geogr. 101, 115–130. https://doi.org/10.1080/00167223.2001.10649455

Sann, V., 2010. Social protection in Cambodia: Toward effective and affordable social protection for the poor and vulnerable, in: Asher, M.G., Oum, S., Parulian, F. (Eds.), Social Protection in East

Asia-Current State and Challenges. Economic Research Institute for ASEAN and East Asia, Jakarta, pp. 316–345.

Scholz, U., 1988. Types of Spontaneous Pioneer Settlement in Thailand, in: Manshard, W., Morgan, W. (Eds.), Agricultural Expansion and Pioneer Settlements in the Humid Tropics. The United Nations University, Tokyo, pp. 44–61.

Schulz, R., Huyssteen, S. van, 1999. Cambodia Report of the Evaluation Mission on two projects: Labour-based infrastructure rehabilitation and Labour-based rural infrastructure development component of the Cambodian area rehabilitation and regeneration. International Labour Organisation United Nations Development Programme, Phnom Penh.

Schut, M., Andersson, J.A., Dror, I., Kamanda, J., Sartas, M., Mur, R., Kassam, S.N., Brouwer, H., Stoian, D., Devaux, A., Velasco, C., Gramzow, A., Dubois, T., Flor, R.J., Gummert, M., Buizer, D., McDougall, C., Davis, K., Homann-Kee Tui, S., Lundy, M., 2017. Guidelines for innovation platforms in agricultural research for development: decision support for research, development and funding agencies on how to design, budget and implement impactful innovation platforms. International Institute of Tropical Agriculture and Wageningen University.

Schut, M., Kamanda, J., Gramzow, A., Dubois, T., Stoian, D., Andersson, J.A., Dror, I., Sartas, M., Mur, R., Kassam, S., Brouwer, H., Devaux, A., Velasco, C., Flor, R.J.O.Y., Gummert, M., Buizer, D., Mcdougall, C., Davis, K., Tui, S.H.-K., Lundy, M., 2018. INNOVATION PLATFORMS IN AGRICULTURAL RESEARCH FOR DEVELOPMENT: Ex-ante Appraisal of the Purposes and Conditions Under Which Innovation Platforms can Contribute to Agricultural Development Outcomes. Exp. Agric. 1–22. https://doi.org/DOI: 10.1017/S0014479718000200

Schut, M., Klerkx, L., Sartas, M., Lamers, D., Campbell, M.M.C., Ogbonna, I., Kaushik, P., Atta-Krah, K., Leeuwis, C., 2016a. Innovation platforms: experiences with their institutional embedding in agricultural research for development. Exp. Agric. 52, 537–561. https://doi.org/DOI: 10.1017/S001447971500023X

Schut, M., van Asten, P., Okafor, C., Hicintuka, C., Mapatano, S., Nabahungu, N.L., Kagabo, D., Muchunguzi, P., Njukwe, E., Dontsop-Nguezet, P.M., Sartas, M., Vanlauwe, B., 2016b. Sustainable intensification of agricultural systems in the Central African Highlands: The need for institutional innovation. Agric. Syst. 145, 165–176. https://doi.org/10.1016/J.AGSY.2016.03.005

Séguy, L., Husson, O., Charpentier, H., Bouzinac, S., Michellon, R., Chabanne, A., Boulakia, S., Tivet, F., Naudin, K., Enjalric, F., Ramaroson, I., Rakotondramanana, 2012. Principles, functioning and management of ecosystems cultivated under Direct seeding Mulch. based Cropping systems (DMC). CIRAD, France, Antananarivo, Madagascar.

Shaner, W.W., 1982. Farming systems research and development : guidelines for developing countries / W.W. Shaner, P.F. Philipp, W.R. Schmehl ; editorial assistance, Donald E. Zimmerman, Westview special studies in agriculture (aquaculture science and policy). Westview Press, Boulder, Colo.

Shi, P., Li, W., 1999. Rehabilitation of Degraded Mountain Ecosystems in Southwestern China: An Integrated Approach. Ambio 28, 390–397.

Sirisambhand, N., 1988. The Forest Colonization Process: Case Studies of Two Communities in North-East and South-East Thailand, in: Manshard, W., Morgan, W. (Eds.), Agricultural Expansion and Pioneer Settlements in the Humid Tropics. The United Nations University, Tokyo, pp. 62–73.

Slaats, J., Lestrelin, G., 2009. Improving cropping systems by introducing conservation agriculture: taking stock of the results and methodology of research-development in southern Sayaboury province, Lao PDR. Programme de Capitalisation en Appui à la Politique de Développement Rural (PCADR), Vientiane.

Sopheapa, U., Patanothaib, A., Ayec, T.M., 2012. Unveiling constraints to cassava production in Cambodia: An analysis from farmers' yield variations. Int. J. Plant Prod. 6, 409–428.

Speelman, E.N., García-Barrios, L.E., Groot, J.C.J., Tittonell, P., 2014. Gaming for smallholder participation in the design of more sustainable agricultural landscapes. Agric. Syst. 126, 62–75. https://doi.org/10.1016/j.agsy.2013.09.002

Stier, K., 1993. Log rolling: Thai forestry contracts help to fund Khmer Rouge. Far East. Econ. Rev. 156, 15–16.

Sum, S., Khiev, P., 2015. Contract Farming in Cambodia: Different Models, Policy and Practice. Cambodia Development Resource Institute (CDRI), Phnom Penh.

Suphanchaimart, N., Wongsamun, C., Panthong, P., 2005. Role-playing games to understand farmers' land-use decisions in the context of cash-crop price reduction in upper northeast Thailand, in: Bousquet, F., Trébuil, G., Hardy, B. (Eds.), Companion Modeling and Multi-Agent Systems for Integrated Natural Resource Management in Asia. International Rice Research Institute (IRRI), Los Baños, Philippines, p. 360.

Systems, A., The, I., Snoo, D., 2018. Opening design and innovation processes in agriculture : Insights from design and management sciences and future directions 165, 111–115. https://doi.org/10.1016/j.agsy.2018.06.004

Taylor, P., 2016. Frontier commoditisation in post-socialist Southeast Asia. Asia Pac. Viewp. 57, 145–153. https://doi.org/10.1111/apv.12125

Tittonell, P., 2014. Livelihood strategies, resilience and transformability in African agroecosystems. Agric. Syst. 126, 3–14. https://doi.org/http://dx.doi.org/10.1016/j.agsy.2013.10.010

Tittonell, P., Muriuki, A., Shepherd, K.D., Mugendi, D., Kaizzi, K.C., Okeyo, J., Verchot, L., Coe, R., Vanlauwe, B., 2010. The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa – A typology of smallholder farms. Agric. Syst. 103, 83–97. https://doi.org/10.1016/j.agsy.2009.10.001

Tivet, F., Boulakia, S.R.I., 2017. Climate Smart Rice Cropping systems in Vietnam. State of knowledge and prospects. Montpellier, France.

Tong, K., Lun, P., Sry, B., Pon, D., 2013. Levels and Sources of Household Income in Rural Cambodia 2012, CDRI Working Paper Series. Phnom Penh. https://doi.org/10.1017/CBO9781316182635.003

Touch, V., Martin, R.J., Scott, F., Cowie, A., Liu, D.L., 2017. Climate change impacts on rainfed cropping production systems in the tropics and the case of smallholder farms in North-west Cambodia. Environ. Dev. Sustain. 19, 1631–1647. https://doi.org/10.1007/s10668-016-9818-3

Touch, V., Martin, R.J., Scott, J.F., Cowie, A., Liu, D.L., 2016. Climate change adaptation options in rainfed upland cropping systems in the wet tropics: A case study of smallholder farms in North-West Cambodia. J. Environ. Manage. 182, 238–246. https://doi.org/10.1016/j.jenvman.2016.07.039

Touk, K., 2004. Could Cambodia's farmers be rich? Lessons learned from the northwest former khmer rouge zones, in: Proceedings of the Seminar on Cambodia's Economy in the Next Five Years: How WTO Accession Could Help Cambodia Accelerate Reforms and Strengthen the Economy. Economic Institute of Cambodia, Phnom Penh, p. 4.

Tran Quoc, H., 2018. Introducing Biodiversity in Banana Systems. Role of the cover crops in the biological control of pests and diseases for a sustainable banana production., in: Agroecology Futures Regional Forum. GRET/CIRAD/MAFF, Siem Reap, Cambodia.

Triomphe, B., Andersson, J., Scopel, E., Juma, M., 2018. Family farming facing the challenges of agroecological intensification Family farming facing the challenges of agroecological intensification, in: Proceedings of the International Encounters on Family Farming and Research Workshop.

Tui Homann-Kee, S., Adekunle, A., Lundy, M., Tucker, J., Birachi, E., Schut, M., Klerkx, L., Ballantyne, P., Duncan, Al., Cadilhon, J., Mundy, P., 2013. What are innovation platforms ? Innov. platforms Pract. Br. 1, 1–6.

Turner, B.L., Meyer, W.B., 1994. Global land-use and land-cover change: an overview, in: Meyer, W.B., Turner II, B.L. (Eds.), Changes in Land Use and Land Cover: A Global Perspective. University of Cambridge, Cambridge, New York, Melbourne, pp. 3–10.

Valbuena, D., Groot, J.C.J., Mukalama, J., Gérard, B., Tittonell, P., 2015. Improving rural livelihoods as a “moving target”: trajectories of change in smallholder farming systems of Western Kenya. Reg. Environ. Chang. 15, 1395–1407. https://doi.org/10.1007/s10113-014-0702-0

van Mierlo, B.C., Augustyn, A.M., Elzen, B., Barbier, M., 2017. AgroEcological Transitions: Changes and breakthroughs in the making, in: AgroEcological Transitions. Wageningen University & Research, pp. 9–16.

Vongvisouk, T., Broegaard, R.B., Mertz, O., Thongmanivong, S., 2016. Rush for cash crops and forest protection: Neither land sparing nor land sharing. Land use policy 55, 182–192. https://doi.org/10.1016/j.landusepol.2016.04.001

Warnars, L., Oppenoorth, H., 2014. Bioslurry: A Supreme Fertiliser A study on bioslurry results and uses.

Wenjun, O., Maofen, L., Aye, T.M., Srey, S., 2016. Current situation of cassava production, constraints and opportunities in Cambodia. Agric. For. Fish. 5, 64–70. https://doi.org/10.11648/j.aff.20160503.16

World Bank, 2015. Cambodian agriculture in transition: Opportunities and risks, Economic and Sector Work, Report No. 96308-KH. Agriculture Global Practice East Asia and Pacific Region, Washington DC.

World Bank, 2012. Agricultural Innovation Systems : An Investment Sourcebook. Agricultural and Rural Development. The World Bank, Washington DC. https://doi.org/10.1596/978-0-8213-8684-2

Wyckhuys, K.A., Hughes, A., Buamas, C., Johnson, A.C., Vasseur, L., Reymondin, L., Deguine, J.-P., Sheil, D., 2018. Biological control protects tropical forests. bioRxiv 391748. https://doi.org/10.1101/391748

Yoeu, A., 2016. Integrating ecosystem services Into agricultural land use Analysis and planning In Mondulkiri province, Cambodia. Montpellier SupAgro.